Geomorphological and environmental studies of karst, northwest Nelson, New Zealand

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Abstract

This study describes the characteristics of the karst terrains and evaluates the surface and subsurface processes operating on the karst systems located between the Takaka and Riwaka Valleys, northwest Nelson, New Zealand. The purpose of this study is to differentiate between natural environmental and human induced changes in the karst system, and where possible, quantify human impacts.

Detailed geomorphological mapping at 1:7500 scale was used to compile an inventory of the karst geomorphology. Geomorphological classification of the surface karst features and an assessment of the lithological and geological variations resulted in the identification of eight karst land systems or zones, in which a similar pattern of topography, hydrology, surface features and soils are recognised. Based on the predominant landforming processes, the karst zones: Kairuru, Takaka Plateau, Canaan South, Canaan North, Pikikiruna, Takaka Walkway, East Takaka and Pohara, are categorised into three groups.

Solution is the dominant process in the first group (Takaka Plateau and Takaka Walkway) which is characterised by internal drainage and a lack of surface streams, rolling topography, numerous, well-formed dolines and karren, and exposed rock surfaces. In the second group (Canaan South, Canaan North, and Pikikiruna), wide karst valleys, numerous alluvial dolines, covered rock surfaces and focused allogenic recharge occur in response to combined fluvial and solutional processes operating on low slope angles. Fluvio-karst processes are also active in the third group, comprising the Kairuru, East Takaka and Pohara zones. This group is characterised by incised karst valleys, mixed drainage systems, steep slopes, and limited doline development. It varies from the low slope - fluviokarst group in that overland flow and lateral solution are common because of the steeper slope gradients.

The eight karst zones are useful management units and the vulnerabilities of the karst to human activities has been evaluated using these zones. The primary impact in the zones of the first group is soil erosion. The presently exposed marble surfaces in these karst zones reflect the loss of 10 - 30cm of soil following land clearance c.100 years ago. The impacts of stream and subsurface sedimentation and water quality degradation dominate in the other zones because of focused runoff, allochthonous soils and higher intensity of land use.

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Acknowledgements

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CHAPTER ONE – INTRODUCTION

1.1 General Introduction

1.1.1 Aims or thesis rationale

The karsts of the Takaka Hill-Riwaka and Pikikiruna Range-Takaka Valley systems are the focus of this geomorphological research and environmental evaluation because development of the karst in these systems is increasing. It is this area of northwest Nelson's karst that the local governing authority (Tasman District Council) considers most under pressure from a diversity of demands and multiple land-uses, including the frequently competing requirements of resource use and conservation. This thesis has two main objectives: firstly, to identify and understand the geomorphological systems of the karst and secondly, to use this understanding of the landforms and karst evolution to assess environmental impacts.

Integrated studies of the functions and characteristics of the karst system are required in order to ensure that planning, use and management of karst is effective and rational. Geological, geomorphological, hydrological and ecological variances in karst throughout northwest Nelson, and throughout New Zealand, mean that karst systems must be independently assessed so that differences in the workings of each can be understood and managed according to local conditions. The geomorphological research of this thesis represents the first attempt at compiling a detailed inventory of karst geomorphology in the Takaka Hill and Pikikiruna Range areas.

This geomorphological inventory and research provides information that assists in identifying environmental changes or impacts in the karst areas. Karst systems are impacted by both natural and human induced environmental change and in many cases they are interacting. Distinguishing the changes to karst systems produced by natural ongoing changes from those caused by human interference, is one of the most important problems to be overcome in assessing environmental impacts (Williams 1993).

The following aims have been developed to aid in guiding this thesis and the research outcomes:

a) define the extent of the karst system in the study area and map the karst landform features
b) identify those landform features or assemblages of features that are characteristic and/or distinctive of the karst terrain(s)
c) establish the geomorphic evolution of the karst landform assemblages

d) determine which karst landform and/or process changes can be distinguished as human induced impact from natural environmental change
e) evaluate the robustness or vulnerabilities of the karst systems and/or landform zones

Environmental studies on karst systems are seen as increasingly important because karst is commonly regarded as being inherently fragile and vulnerable to impacts from environmental changes. Karst requires specific management, and poses many problems to land managers, because of its unique surface and subsurface systems, hydrology and fragile ecological conditions (Williams 1993). The study of karst environmental systems, and the vulnerability or robustness of those systems, are especially important in preventing ecosystem degradation. Management and land use practices developed for conventional catchment conditions are often not relevant to karst with its distinctive surface and subsurface systems (Williams 1993).

Components of the karst system especially susceptible to adverse impacts are karst aquifers and soils. Groundwater systems in karst are unusual in that the hydrological conditions vary considerably and flow-through rates are often very fast. The notion that water rising from springs is filtered and clean or 'pure' does not often apply in karst areas. Pollutants are easily introduced via surface inputs and are transported with little filtration (Smith 1993). In addition, Williams (2001) notes that the large conduit sizes and subsequently rapid flowthrough times mean that, unlike other groundwater systems, bacteria can survive subsurface transport (bacteria can live underground for 10-30 days). He also, perhaps surprisingly to many, states that while karst springs may look clear and appealing, "there are few in New Zealand that are safe to drink without first boiling the water" (Williams 1992b, pp205).

Soil denudation is of primary concern in karst areas and provides a focus for the environmental impacts evaluation in this research. Karst soils develop very slowly because solution is the dominant geomorphic agent and there is a resultant lack of weathering residues (Ford and Williams 1989). The often thin veneer of soils in karst regions is prone to soil degradation and erosion. The problem of soil denudation is compounded by the nature of the karst itself, which promotes vertical transportation of soils/surface material via surface openings such as dolines and fractures (Williams 1992b, Ford and Williams 1989).

1.1.2 Location of study area

The study area covers the marble karst systems of the Takaka Hill-Riwaka and Pikikiruna Range-East Takaka karsts, and those limestones of the Clifton, Motupipi, Pohara and Tarakohe areas which lie close to the Pikikiruna fault scarp (Figure 1.1). The study area is approximately 15 km west of Motueka township and less than 5 km east of Takaka.

Figure 1.1. Location of the Karst Study Area (within red outline), showing topographical detail, northwest Nelson, New Zealand. (Topomap 262-9, Nelson 1:250 000, Department of Survey and Land Information, New Zealand. Crown Copyright Reserved.)

The marble study area has an approximate extent of 25 km in length and 10 km at the widest point. Some areas of the karst with restricted or denied field access were reviewed using remote methods only.

The karst comprises part of the larger northwest Nelson karst systems and the marble ranges are a northerly extension of the Mount Arthur Ranges. The marble karsts occur as part of the Ordovician Marble massif, which extends for approximately 100 km south of the Golden Bay coast. The Pikikiruna Fault Scarp, a kilometre high escarpment that forms the eastern boundary of the Takaka Valley, bounds the marble to the west. The study area is bound to the east by granites of the Separation Point Batholith. State Highway 60, crossing the Takaka Hill, defines the south-east edge of the study area (Figure 1.1).

The limestones researched in this thesis comprise the Pohara limestones and the Clifton – Motupipi, limestone ridge running parallel to the Pikikiruna fault scarp. Limestones presently influenced by coastal processes were not included in this study.

Selection of the study area as a suitable site was made because of the accessibility and range of karst environments within a manageable area for field mapping. The area hosts a range of land uses including residential property, agriculture, national park and reserve areas and state highway roading.

1.2 Karst

1.2.1 Definitions and distinctiveness

Karst is terrain in which relatively high rock solubility and the development of underground drainage interract to form distinctive surface and subsurface landforms. Characteristic landforms and hydrologic features include enclosed depressions, blind valleys, disappearing streams, springs, caves, and sculpted rock outcrops.

Karst–like terrains with sinking streams, springs and sinkholes in which the landforms are not produced by solution are termed pseudokarst. In New Zealand pseudokarst is mainly confined to the glaciers of the South Island and to the volcanic regions of the North Island where, for example, caves are found in lava tubes (Williams 1992).

The word 'karst' has its derivatives in several European words such as *karra* meaning stone, and *kars* or *kras*, a Slovenian (Yugoslavian) word meaning barren, stony and waterless ground. Kras or Karst is also a classical karst region on the Slovenian/Italian border and was one of the early type sites for scientific karst study (Ford and Williams 1989). Because karst terms and words are found in the literature of many languages there is often a profusion of karst definitions. A glossary of selected karst terms is presented at the end of this thesis.

That karst landscapes are distinct from other landscapes arises because karst rocks are relatively highly soluble in natural waters and leave little weathering residue (Cooke and Doornkamp 1990, White 1988). The formation of karst in carbonate bedrock involves the dissolution of rock by acid. Rain falling through the atmosphere dissolves carbon dioxide (CO_2) into droplets. Moving through the soils the rainwater picks up more CO_2 to form a weak solution of carbonic acid ($H_2O + CO_2 = H_2CO_3$). These slightly acidic waters infiltrate any existing joints or fractures, and corrode the carbonate rock. The dissolution of carbonate rock by carbonic acid can be summarised in the following equation: $CaCO_3 + CO_2 + H_2O = Ca^2 + 2HCO_3$. Infiltrating waters enriched with CO_2 exploit the existing structures in the rock and along with mechanical abrasion caused by running waters, enlarge the openings creating conduits, caves and a complex underground drainage system (Ford and Williams 1989).

Karst is best developed in hard, non-porous rocks comprised of >50% carbonate such as limestone, marble, and dolomite or less commonly, in gypsum and rock salt deposits (Williams 1992). Ford and Williams (1989) note that not all rocks with relatively high rock solubility develop the distinctive karst features. Carbonate rocks with high primary porosity often have poorly developed karst, because a crucial component to karst formation is the development of secondary porosity, often along structural features. These structures provide solution pathways down which the vertical karst drainage can develop. Thus, carbonate rocks with very low primary porosity that have since formed marked secondary porosity, such as the Arthur Marble, support excellent karst (Ford and Williams 1989).

Carbonate rocks comprise approximately 12-20% of the Earth's ice-free landmass (White et al. 1995, Williams 1993). Ford and Williams (1989) estimate that, as not all carbonate rocks form the distinctive or characteristic karst landforms and hydrology, the extent of karst is only ~ 7-10% of this surface. It is interesting to note that although karst only makes up a relatively small percentage of the earth's rocks, it has been estimated that one-quarter of the world's population obtain their water from karst aquifers (Ford and Williams 1989).

Karst is thus widely valued for its unique landform features and often abundant groundwater resources. Other reasons the karst is valued include;

- As habitats for unusual and/or endangered species of flora and fauna (particularly subterranean adapted or troglobitic organisms)
- As important sites for earth science and natural history research, especially cave deposits considered as undisturbed 'time vaults' containing fossils, sediments, and human artefacts
- As sources of economically important resources, including water, soils, agricultural and processing applications, building material, and repositories of ore minerals, oil and gas

- As culturally or spiritually significant places, to indigenous peoples and visitors alike
- For locations containing rare minerals
- For tourism and the associated economic benefits, with people enjoying the area for scenic values or cave exploration
- As purely recreational areas, both passive and active

(New Zealand Department of Conservation 1999, IUCN Commission on National Parks and Protected areas 1996).

More detailed information on karst and karst systems can be found in Ford and Williams (1989), White (1988), Trudgill (1985), Sweeting (1973) and Jennings (1971). Studies pertaining to karst environmental systems and karst management can be found in the IUCN Commission on National Parks and Protected areas (1996), Williams (1993), Beck (1993, 1989, 1987), Cooke and Doornekamp (1990), Daoxian (1988), Gillieson (1989, 1988), and Kiernan (1988). The increasing attention and research in this area is highlighted by these papers, in particular, the collection of essays on environmental changes and impacts on karst edited by Williams (1993) and the IUCN-World Conservation Union's (1996) cave and karst management guidelines.

1.2.2 Karst in New Zealand

Karst landscapes are relatively less widespread in the southern hemisphere (Ford and Williams 1989) and in New Zealand form only around 1% of the total landscape (Millar 1997). Within New Zealand, karst terrains vary widely from the large extents of the subalpine marble ranges of northwest Nelson and the lowland karst of the West Coast Paparoa Syncline, through to occasional, minor limestone outcrops (New Zealand Department of Conservation 1999). Apart from the Ordovician marble, and the lone dolomite outcrop at Collingwood (both in northwest Nelson), karst in New Zealand is predominantly hosted by Oligocene limestones (Figure 1.2). Not all of the carbonate outcrops distributed throughout New Zealand have sufficient lithological characteristics to be conducive to karst formation (Williams 1992). Hence, the principal karst areas in New Zealand are the:

- North-west Nelson Marble, including the Owen and Arthur Ranges and the Takaka Hill-Riwaka and Pikikiruna Range-Takaka Valley systems
- West Coast of the South Island, limestones at Paturau, Karamea and Punukaiki
- Western Waikato-King Country region, limestones including Waitomo (Maniapoto karst).

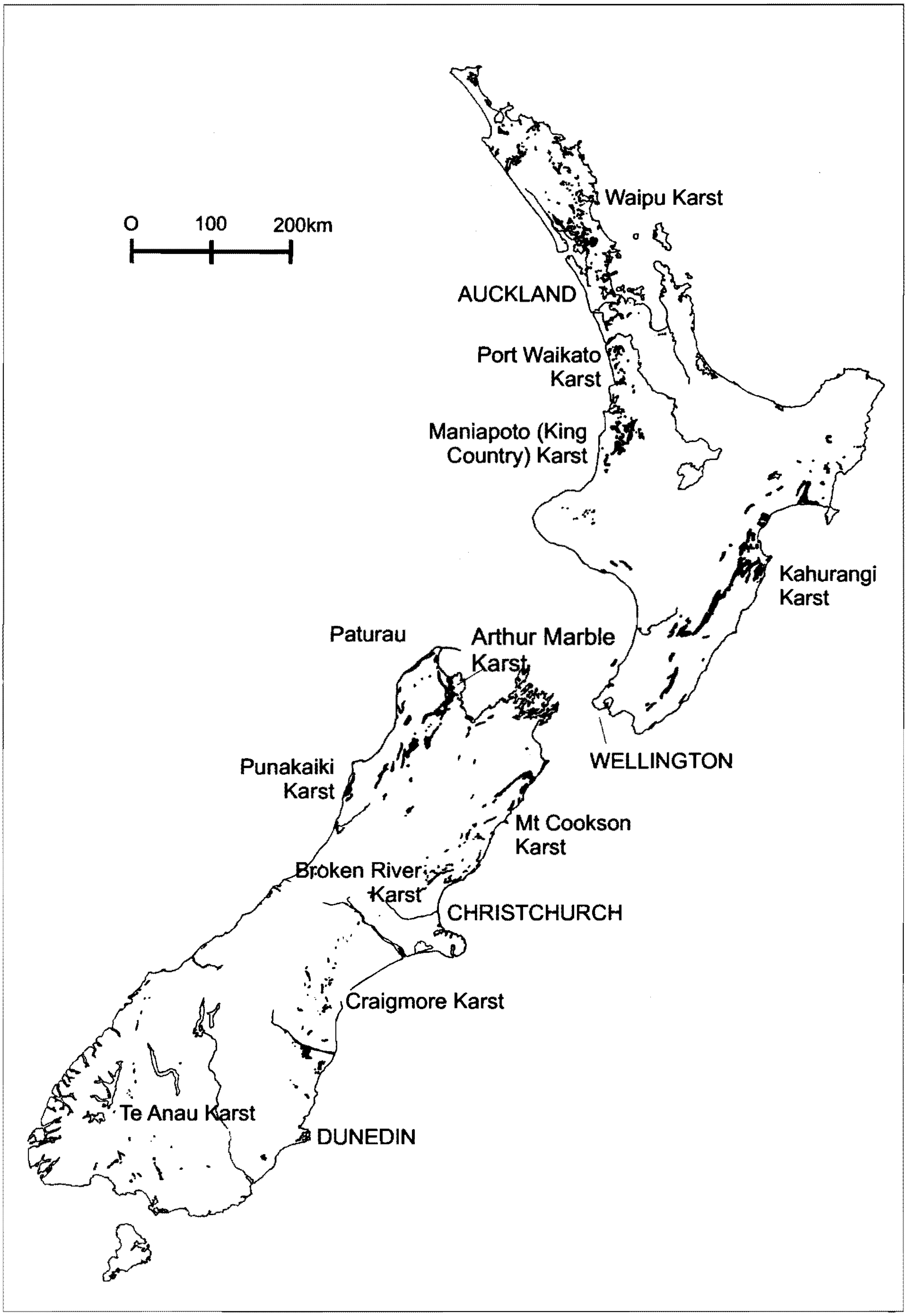


Figure 1.2 Distribution of carbonate rocks in New Zealand. (Williams 1992)

1.2.3 Karst in northwest Nelson

According to Williams (1992b), the karst terrains of northwest Nelson provide both the most spectacular karsts (Figure 1.3) and important karst aquifer in New Zealand. Certainly the karst systems and selected landforms are considered a major karst resource of regional, national and international importance (New Zealand Department of Conservation 1999, Hayward et al. 1999, Worthy 1990). The carbonate rocks of the Arthur Marble host karst systems with much greater relief and deeper karstification than any of the other carbonate terrains in New Zealand. They support New Zealand's largest spring (Waikoropupu Springs), the deepest, longest, and possibly oldest caves such as Nettlebed (889m deep, 25km long, and over 700 000 years old), and the largest subterranean rivers in the country (New Zealand Department of Conservation 1999, Williams 1992b). Williams (1992b) provides a good general review of the most significant karst features and characteristics throughout the Tasman region and New Zealand. The karsts of the Takaka region are renowned for features such as the 176m free-fall shaft of Harwoods Hole, the scenic Marble Plateau Karst (visible from Highway 60 over the Takaka Hill), and the resurgence or source of the Riwaka River. Furthermore, the Takaka-Riwaka karsts are particularly enticing to cavers (or speleologists) due to the numerous and extensive cave systems such as Greenlink (approximately 360m deep), Middle Earth, and Perseverance. The often impressive cave deposits including stalactites, stalagmites and flowstones (such as those found in Rawhiti Cave), known collectively as speleothems, attract speleologists and tourists alike. The variety and number of caves within the northwest Nelson area has attracted both speleological exploration and research into the cave and karst features. Aside from the well documented and detailed maps of caves in the area produced by the New Zealand Speleological Society, studies focusing on registering karst forms of regional, national or international importance include Hayward et al. (1999), Worthy (1990), and Millar and Rautjoki (1984).

Authors such as Edgar (1998), Mueller (1992, 1987) and Williams (1992a) have researched the hydrology of the Takaka – Golden Bay area, which is dominated by karst aquifers. Research in the area is often focused on Waikoropupu Springs, and the associated Takaka Valley aquifers and discharges (Mueller 1991, Stewart and Williams 1981, Williams 1977). Williams and Dowling (1979) and Dowling (1974) cover aspects of karst hydrology and solution processes within the Takaka Hill – Riwaka area. Despite this list of studies the complex hydrological systems in the karst are little understood. Karst areas consist of two dynamically interconnected landscapes, a visible surface landscape and a frequently

Figure 1.3. Karsts of the study area. (a) Undulating marble plateau of the Takaka Hill (Takaka Plateau) with numerous, large solution dolines forming the characteristic karst relief. Solution sculptured rocks or karren (as seen in the foreground) are widespread throughout the karst terrains. The blue coloured hills in the background are the granitic Pikikiruna Ranges and Otuwhero Hills. The photo is taken from State Highway 60 near the Canaan Road turnoff. (b) The imposing Pikikiruna fault escarpment (East Takaka), uplifted by up to 1km and incised by karst gorges, forms the eastern side of the Takaka Valley. The Takaka Limestone Ridge, folded near vertical by the Pikikiruna fault lies in the foreground. The photo is taken from Packards Road, Motupipi.

inaccessible or alien subsurface system. The surface and subsurface systems may each have relatively unrelated catchment areas and hydrological characteristics. Underground waterways do not conform to the usual hydrological rules followed by surface streams and can flow in directions contrary to the topography. This means that the boundaries of a karst system often extend beyond the apparent outcrop of the karst rocks and into non-carbonate lithologies (Williams 1993). Some hydrological connections in the Takaka Hill karst systems were identified by fluorescein dye tracing, the results are briefly presented in Dowling (1974) and Williams and Dowling (1979). Aside from the Riwaka Basin (Dowling 1974), hydrological research has yet to delineate the internal karst catchments or identify many of the hydrological connections within the karst systems, particularly the Pikikiruna Range and Takaka Limestone karsts.

Literature pertaining to the issues surrounding conserving and preserving these karst resources includes the New Zealand Department of Conservation (1999), Tasman District Council (1998), Williams (1987), and Wilde (1986). The documents presented by the New Zealand Department of Conservation (DOC) and the Tasman District Council (TDC) examine both the policies and action required in managing karst terrains. Williams (1987) discusses the distribution of karst rocks in relation to National Park status and the challenges presented by subterranean systems, while Wilde (1986) reviews the effectiveness of karst conservation within formal reserves.

1.3 Human Impacts and karst management

1.3.1 Human impacts on karst

The principal human activities that interact with the karst systems in the study area are agriculture, plantation forestry, residential development, road and communication installations, mining, tourism and recreation. Some of these activities may adversely effect features in karst systems such as water quality, soils, vegetative cover, and subterranean systems and deposits. Most landowners and land managers would agree that the desired goal of karst management is a sustainable balance between use and conservation. Unfortunately it often seems that when one operation proceeds, the other is detrimentally affected. The two may be considered as interdependent. For example, economic prosperity aids in providing resources for conservation activities while good quality aquifers and productive soils are a necessary component of on-going economic projects such as farming and forestry.

1.3.2 *Management approaches to karst*

The importance of karst in the northwest Nelson area and the need to conserve values within the area was formally recognised by the inclusion of karst, and adjacent catchment areas, in the Abel Tasman National Park (Figure 1.4). Several karst areas including the Gorge Creek – Harwood's Hole – Starlight Cave system were acquired from the State Forests Service and added to the park in 1977 (Rennison, G. *pers.comm.* 2002). This constituted the first deliberate effort to include karst features within a national park (Wilde 1986). Other areas such as the Waikoropupu Springs Scenic Reserve and the Takaka Walkway Trust Area have been established with the purpose of protecting and highlighting karst features (Wilde 1986, Harwood, D. *pers.comm.* 2002).

The Tasman District Council (TDC), along with a Karst working group, comprising local landowners, speleologists and other interested parties, have been more recently, working towards developing a karst management plan as part of a wider Tasman Resource Management Plan (TRMP). As both a regional council and a territorial authority, the Tasman District Council, under the Resource Management Act 1991, is required to implement plans to promote the sustainable management of natural and physical resources. The Council proposed the TRMP in 1998 with provisions made for karst terrains including land disturbance, discharges to land and water, and landscape. The plan recognised the karst as a 'naturally high risk terrain' and identified vegetation, soils, pavement surfaces and streams as requiring careful management (Tasman District Council 1998). Methods proposed in the TRMP to address issues and assist in implementing policies include:

- (i) Investigation and monitoring, generating information about resource use and environmental effects
- (ii) Advocacy and education, providing information and promoting preferred practices
- (iii) Works and services, to avoid, remedy, or mitigate any adverse effects
- (iv) Financial measures, including charges and incentives
- (v) Regulation, using rules, consents, and self regulatory actions
- (vi) Taking no action, where results may be achieved without TDC intervention

Although the TRMP is based on managing actual or potential adverse environmental effects (Tasman District Council 1998), the methods for achieving sustainable management may require monitoring or control of human activities. This has caused some disquiet among private landowners of karst terrain.

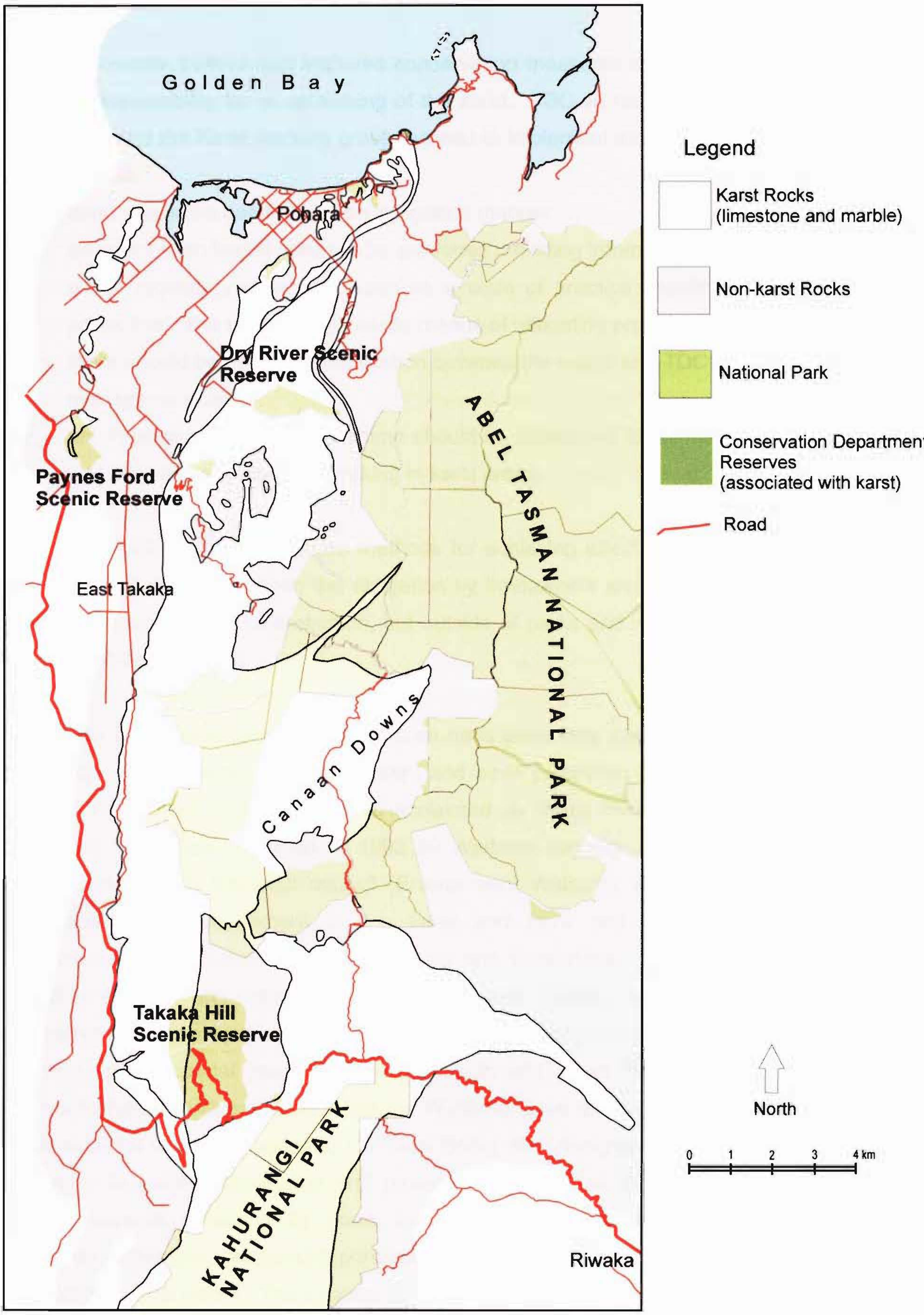


Figure 1.4. National Park and reserves in study area, showing relation of protected land to karst.

Many landowners believe that imposed conservation measures do not recognise their own on-going responsibility for or caretaking of the karst. TDC, in response to discussions with landowners and the Karst working group, agreed to implement the following initial strategies for karst areas:

(a) karst should be dealt with in an integrated manner

(b) an information leaflet needs to be produced providing information on karst

(c) a non-regulatory approach, such as a code of practice should be used for karst protection. The code would include means of mitigating problems

(d) there should be good communication between the public and TDC on matters of karst management, and

(e) an on-going education programme should be introduced for all management, service and contractual personnel working in karst areas.

While the TRMP or the appropriate methods for achieving effective management is still in consultation, it does not lessen the obligation by landowners and managers to ensure that karst phenomena worthy of protection, but outside of parks and reserves, are appropriately managed (Williams 1987).

Community based management programmes have been very successful in protecting karst resources. The Waitomo karst catchment and cave protection plan, implemented by the Waitomo Catchment Trust Board, was acclaimed by those involved as very positive. A Catchment Trust Board, formed in 1992 by Waitomo farming, tourism and conservation interests, along with the local council (Environment Waikato), was set up to encourage sustainable land management of the karst and cave and in particular, to reduce sedimentation of the waterways, both surface and subsurface. The catchment and cave protection scheme was initiated as a trial 'Landcare' project, developed as a grassroots approach to land management where local communities take the incentive in identifying and resolving environmental issues (Waitomo Catchment Trust Board 2001). While the community had incentives in protecting the Waitomo Cave environment because of tourism and associated economic benefits, the Trust Board also recognised the importance of land and water to income generation and protection. The Trust Board has achieved works directed towards achieving its goals by permanent retiring and fencing of farmland (especially gullies and steeplands), purchasing of native forest, and construction of dams and reticulated water supplies. The success of the scheme in stabilising soil, protecting bush and riparian zones, and enhancing the Waitomo Stream has relied on financial contributions made by local authorities and landowners, businesses, and charitable organisations, and most importantly, the enthusiasm and participation of community members (Waitomo

Catchment Trust Board 2001). The Ministry for the Environment (2001) has reviewed the Waitomo Catchment scheme in a recent publication on 'Managing waterways on farms'.
The recent move towards more formal procedures designed to mitigate geomorphic hazards and to protect important values in karst areas outside formal reserves is also reflected in international karst management programmes such as those developed in Tasmania and British Colombia. A river management planning process and karst catchment strategy is presently being developed at Mole Creek, Tasmania (Eberhard and Houshold 2002). The recognition of the management difficulties and complex relationships between surface and subsurface systems is an important aspect of the strategy. Management guidelines and recommended standards for forestry operations, developed with the aim of maintaining the integrity of karst resources by promoting appropriate practices when working in karst terrain, were implemented in Tasmania in 1985 (Kiernan 1988) and very recently in British Colombia (Forest Practices Branch 2002).

1.4 Thesis format

The following chapter, Chapter two, provides background material used during the collation of information for this thesis, including geological, hydrological, and climatic summaries. The material is provided to order to assist in understanding interpretation and discussions presented in later chapters

Chapter three outlines the methods used in gathering and analysing information collected during the geomorphological mapping and classification, lithological sampling and environmental impacts evaluation.

Chapters four and five cover the observational and quantitative data collected from field and laboratory work. More specifically, chapter four presents the results from the detailed geomorphological mapping and outlines the field criteria and attributes observed in the karst landform assemblage zones.

Chapter five presents the results of the geomorphological classification and lithological sampling. The data was used to validate observations made in identifying the landform assemblage zones and in evaluating which karst features are characteristic of each area or karst system.

The evolution of karstification and a review of the main controls on landform development are given in chapter six. Discussions in this chapter focus on the relations between the observed karst landforms and their distribution in the karst zones.
Chapter seven presents the qualitative and quantitative environmental information used to identify and assess human induced environmental changes. Discussions focus on the impacts on the karst terrain from the effects of human activities and highlight the vulnerability of the karst to the more pervasive impacts, particularly soil degradation and sedimentation.

Concluding statements and recommendations for further work are given in chapter eight.

A glossary of selected karst terms is presented at the end of the written section. Information, data and statistical workings pertaining to the research are given in the appendices.

CHAPTER TWO - PROJECT BACKGROUND

2.1 Introduction

In order to understand some of the later interpretations and discussions relating to karst geomorphology and environmental impacts, general information relating to the study area is presented in this chapter. Chapter two, therefore, aims to:

- outline the major topographical features of the Takaka Hill, Pikikiruna Range and Pohara areas
- describe the geology and stratigraphy of the area, outlining the structural features, within the context of the regional northwest Nelson setting
- identify the major hydrological systems within the study area, outlining the regional karst aquifers, their recharge sources and discharge locations
- describe the characteristics of calcareous and non-calcareous soils
- summarise climatic and floral/faunal characteristics, and
- provide a summary of the historical development and present land uses within the study area

The information presented is spatially limited to the area of, and immediately surrounding, the study area, namely the Takaka Hill and Riwaka Valley, the Pikikiruna Range – East Takaka Escarpment, and the Motupipi, Clifton and Pohara sections of the Takaka Valley.

2.2 Topography

The topography of the study area varies from the peaks and plateau of the Takaka Hill – Pikikiruna Range to the undulating coastal and fluvial terraces of the Takaka and Riwaka Valleys (Figure 1.1).

The Takaka Valley is located in a fault-bounded depression, narrowing to the south, with the dissected Tasman Mountains forming the western margin of the valley, and the steep, linear Pikikiruna fault escarpment forming the east. The downstream sections of the Takaka River follow the valley floor, with the flows prone to disappearing underground during the summer months.

The Pikikiruna fault escarpment, up to 1000m high, separates the Takaka Valley from the upland marble karstic plateau and the Pikikiruna Range. The Pikikiruna Range, which runs almost the entire length of the study area, is comprised of granites and metamorphic rocks forming peaks over 1000m. The Range creates a topographic divide between the lower, undulating marble plateau of the Canaan – East Takaka areas in the north and west, and the

Takaka Hill plateau in the southeast. The Canaan karst area lying inland on the karstic plateau forms rolling downlands at approximately 700 - 800m. To the west of Canaan the marble surface is deeply incised by narrow, scree-covered, westerly trending gorges that exit through the steep-sided Pikikiruna fault escarpment.

The sub-alpine Takaka Marble Plateau lying at around 600 m falls away abruptly in the south to form the headwalls of the Riwaka Valley, which lies to the southeast of the study area near to sea level. Drainage trends southeast. Emerging from the head of the valley is the Riwaka north branch resurgence or source of the Riwaka River (Figure 1.1).

The limestone-dominated coastal areas of Pohara and Tarakohe areas, to the very north of the study area, on the downslope side of the Pikikiruna fault scarp are mainly comprised of rolling fluvial and coastal terraces. A prominent, outcropping ridge of Takaka Limestone (locally referred to as the 'hogback') runs along the front of the Pikikiruna fault scarp forming a secondary scarp surface in the Pohara - Clifton – Motupipi areas. Sea cliffs (up to 100m) eroded into the Takaka Limestone dominate the coastal boundary. The sea cliffs form the coastal – land surface boundary of Tasman Bay.

2.3 Geology

2.3.1 Regional setting

New Zealand is divided, geologically, into two distinct provinces – the Western Province and the Eastern Province (Figure 2.1). Each province can be sub-divided into multiple, tectonically and stratigraphically distinctive, fault-bounded terranes (Jongens 1997, Rattenbury et al. 1998). The Western Province is interpreted as a marginal fragment of Gondwanaland that detached during the formation of the Tasman Sea and is now stitched to the terranes of the Eastern Province by the Median Tectonic Zone. The Western Province is comprised of the Early Paleozoic Takaka and Buller terranes. The two terranes are separated by the Anatoki Fault (Rattenbury et al. 1998).

The Takaka terrane, in which the study area lies, consists of a varied assemblages of rocks and ages and can be further subdivided into the east and central parts - formerly the Eastern and Central Sedimentary Belts (Rattenbury et al. 1998). The Takaka terrane is comprised of at least 13 north-south trending fault bounded slices, each with internally consistent stratigraphy (Jongens 1997). The rocks of the Takaka Hill - Pikikiruna Range lie within the Pikikiruna Fault slice, the eastern most structural slice of the Takaka terrane (Rattenbury et al. 1998).

Figure 2.2. provides an illustrative summary of the geological evolution of the terranes and basement rocks of northwest Nelson.

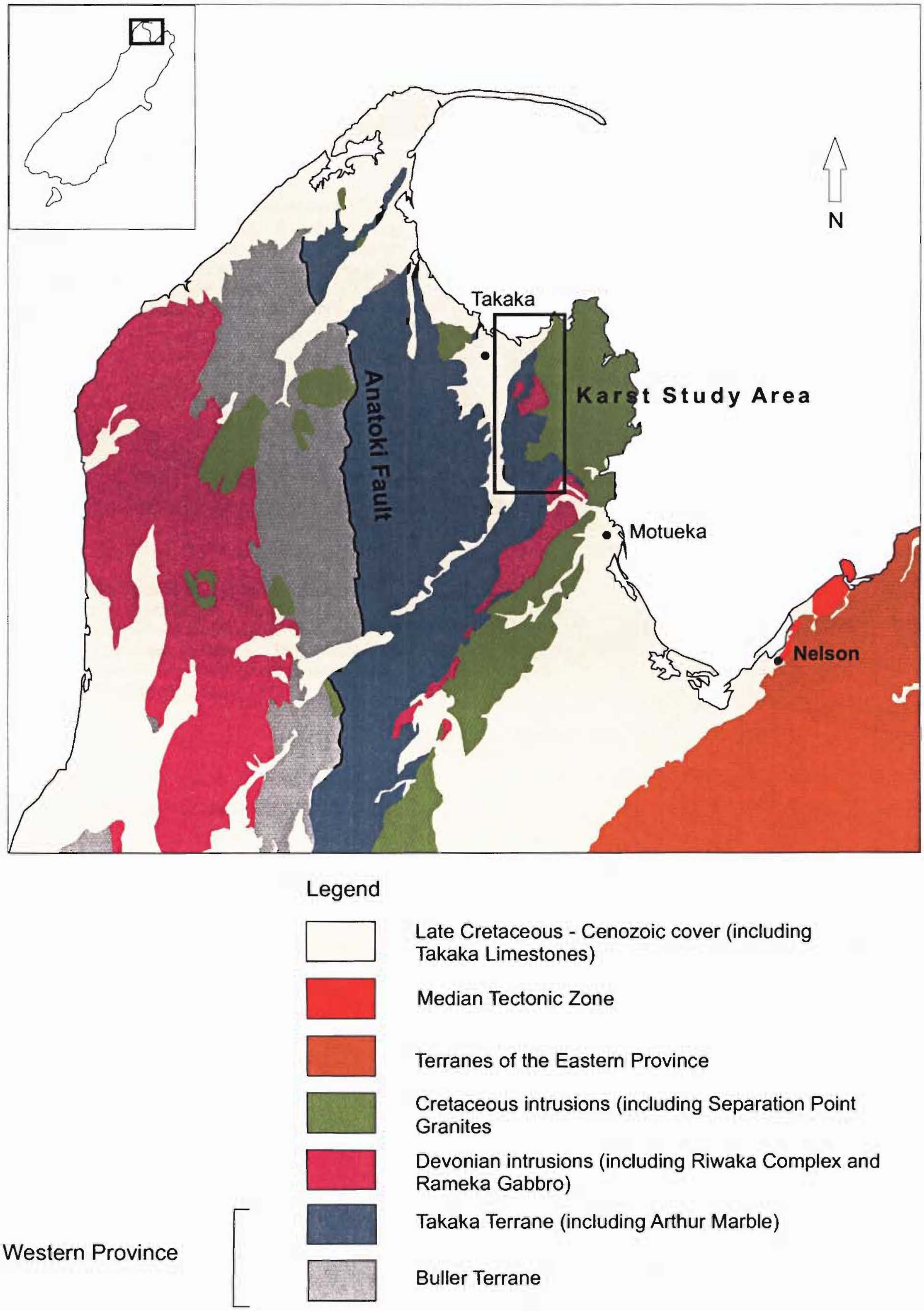
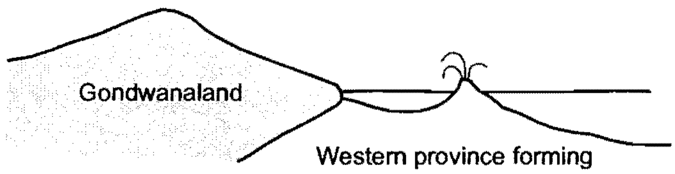
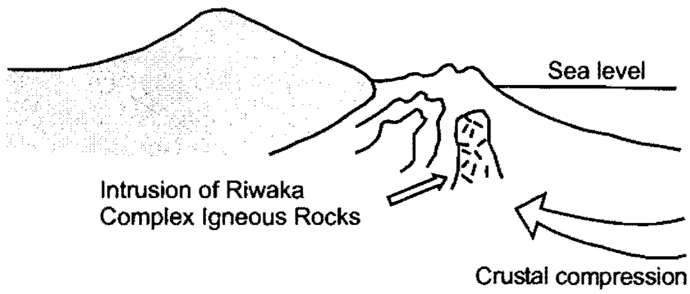


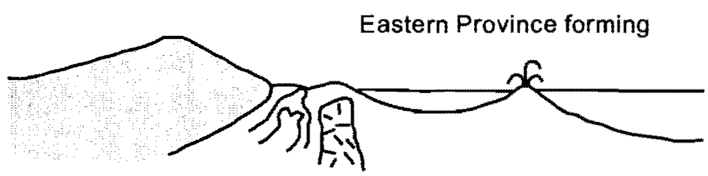
Figure 2.1. Geological provinces and terranes, northwest Nelson, New Zealand (modified from Rattenbury et al. 1998)



a) 600-380 million years ago - Period of land-building in association with volcanism and sedimentation. Land forming part of Gondwanaland or earliest New Zealand (present day north-west Nelson). Limestone deposited during this period of sedimentation (now Arthur Marble).

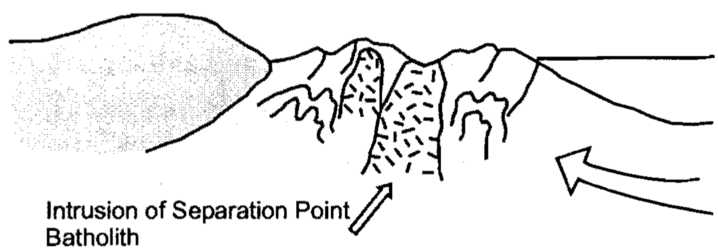
b) 370 million years ago - Collision and uplift of land during Tuhua Orogenic Event creating Western province of present-day New Zealand. Metamorphism of the Arthur Marble occurs prior to the intrusion of the Riwaka Complex. These rocks form the basement of the study area.

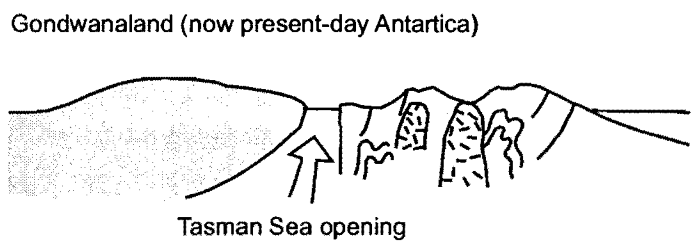




c) 300-110 million years ago - Second sequence of crust-building (volcanism and sedimentation) occurring during on-going subduction, creating present day Eastern Province of New Zealand.

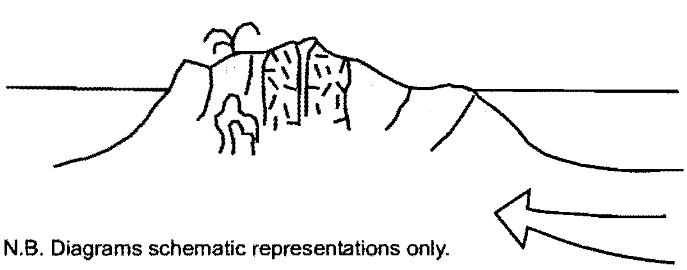
d) 105 million years ago - Marks culmination of collision and accretion (Rangitata Event) which caused the new land mass to collide with the existing Western Province. The Western and Eastern provinces are stitched together by the Separation Point Batholith





e) 105-55 million years ago - Crustal extension and separation. Opening of the Tasman Sea (rifting) causing break-up of NZ edge of Gondwanaland. Erosion of land mass commences.

f) 55-25 million years ago - Rifting of the Tasman Sea stopped. Continuing erosion and marine transgression of the New Zealand land-mass (reflected in still visible peneplain surface). Most of north-west Nelson was under-sea at this time and the Takaka Limestone was deposited during this period.



N.B. Diagrams schematic representations only.

g) 25 million years ago to the present day - Renewed uplift and tectonism (Kaikoura Orogeny) bringing existing landmass out of the sea. Continuing deposition of Tertiary sediments during this phase and the Pikikiruna Range formed by uplift on the Pikikiruna Fault (not shown).
Gravels formed and deposited by glaciers (<2 million years ago) now overly the earlier sequences in some places.

Figure 2.2. Illustrative geological evolution of north-west Nelson, New Zealand (adapted from Thornton 1995)

2.3.2 Lithology and stratigraphy

The Takaka Hill and East Takaka plateau between Motueka and Takaka in northwest Nelson are composed primarily of the Arthur Marble and metasedimentary Pikikiruna Schist. Intruding the above sequence are the igneous Rameka Gabbro, Canaan Granodiorites and the Separation Point Batholith. Outcropping towards the southeast are the Onekaka Schist and Riwaka Igneous Complex (Shelley 1981). The local stratigraphy and stratigraphic relations are summarised in Figure 2.3.

Of foremost interest to this thesis is the karst terrain composed in the main of Arthur Marble (Figure 2.2.a), comprising limestone, pervasively altered or metamorphosed to marble and interbedded with calcareous mudstone and sandstone. The Ordovician Arthur Marble together with the Wangapeka Formation - composed of siltstone, quartz sandstone, calcareous siltstone and carbonaceous shale, forms the Mount Arthur Group (Rattenbury et al. 1998). The marble within the study area is shown by Rattenbury et al. (1998) as Arthur Marble 2, a Late Ordovician black limestone and calcareous mudstone (Figure 2.3).

Outcrops of the Pikikiruna Schist lie to the east of the Pisagh Fault and adjacent to the Separation Point Batholith. The age of the Pikikiruna Schist relative to the Arthur Marble has not been resolved. Shelley (1981) correlated the Pikikiruna Schist with the Silurian Hailes Quartzite and interprets the Schist as metamorphosed Ellis Group sediments (thus younger than the Arthur Marble) emplaced underneath the Arthur Marble by recumbent folding. Other authors (Rattenbury et al. 1998, Grindley 1971) represent the Pikikiruna Schist as relatively older Mount Arthur Group metasediments. Concordantly overlying Arthur Marble 2 is the siliceous biotite-muscovite schist and quartzite bands of the Onekaka Schist (Rattenbury, et al. 1998). The Onekaka Schist outcrops to the southeast of the study area and forms the uppermost unit of the Arthur Marble Group (Figure 2.3).

Intruding the Paleozoic sedimentary strata are the Late Paleozoic to early Cretaceous intrusive rocks of the Riwaka Complex and Separation Point Suite Granites. The Riwaka Complex (Figure 2.2.b), described by Rattenbury et al. (1998) as mainly pyroxenite, gabbro, and diorite, is a Late Devonian mafic and ultramafic complex, which includes the cross cutting plutons of the Rameka Gabbro (Shelley 1991, Cooper 1989). The younger and more widespread Separation Point Batholith (Figure 2.2.d) cuts across both the Paleozoic basement rocks and the Riwaka Complex (Rattenbury et al. 1998, Cooper 1989) and is located on the eastern boundary of the study area. Emplaced during the Cretaceous, the Separation Point Batholith is comprised of composite granites and granidiorite plutons of the Separation Point Suite Granite (Rattenbury et al. 1998, Cooper 1989).

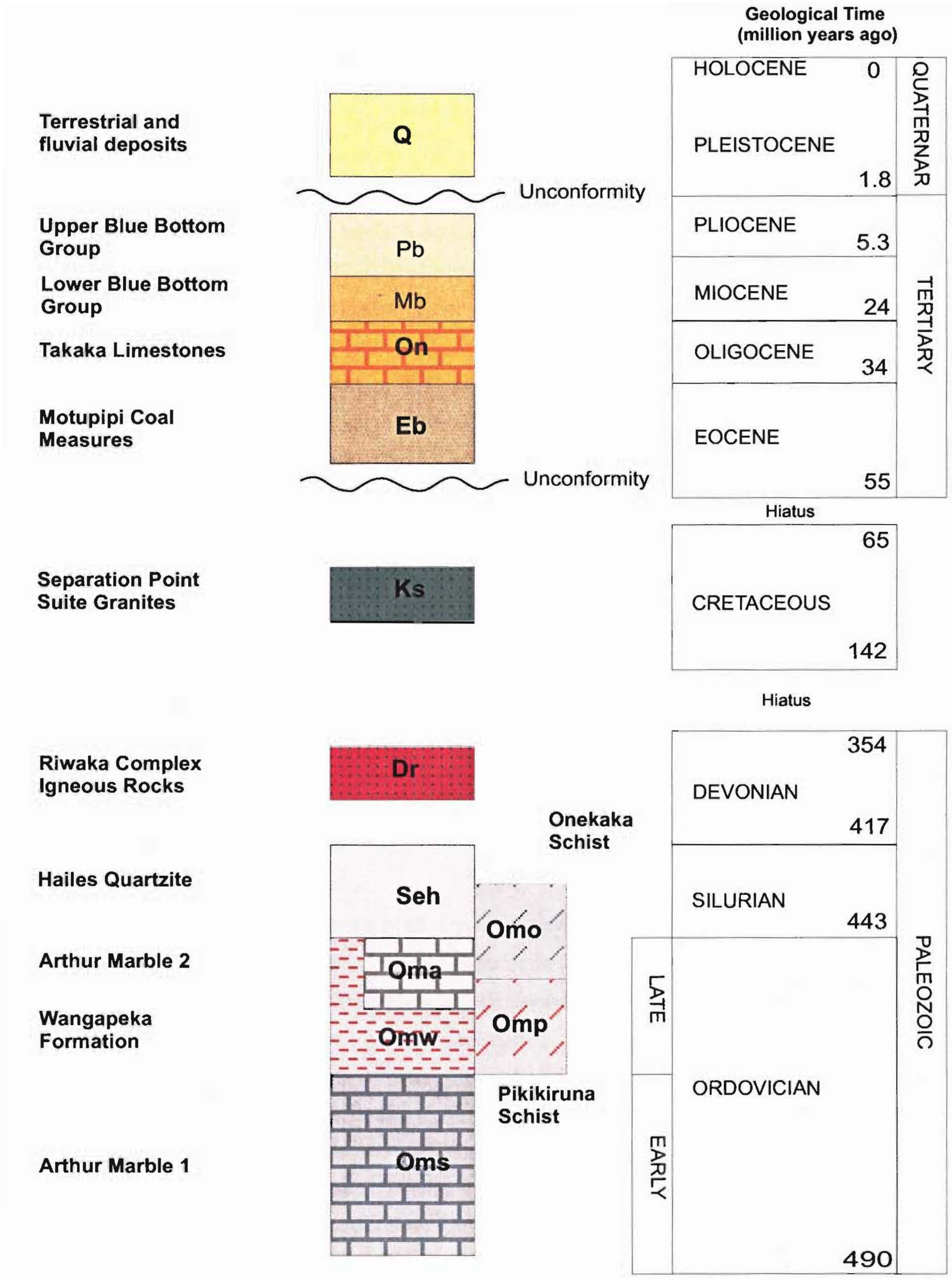


Figure 2.3. Stratigraphic Sequence showing geological units and relative ages. Not to scale. (adapted from Rattenbury et al. 1998)

The next youngest rocks in the area, the Late Cretaceous to early Tertiary Brunner Coal Measures, represent a period of non-marine sedimentary deposition. The Brunner Coal Measures (referred to in the Takaka area as the Motupipi Coal Measures) overlie weathered basement rocks (Rattenbury et al. 1998). The weathering of the basement rocks occurred during a period of tectonic quiescence and erosion (Figure 2.2.f-g) marked in the area by a peneplanation surface that post-dates the formation of the Tasman Sea. Rattenbury et al. (1998) gives this unconformable surface as Early Eocene (from at least 55 to 40 Ma).

Ravens (1990) summarises the tertiary stratigraphy, comprising three units;

(1) The Eocene-Oligocene Motupipi Coal Measures comprise a basal conglomerate, sandstones, siltstones, and coal seams overlying weathered Paleozoic basement. The coal measures are thickest in the east of the valley with up to 350m noted to the west of the Pikikiruna Fault (Rattenbury et al. 1998). (2) The Oligocene to Early Miocene Takaka Limestone (forming part of the Nile Group) conformably overlies the coal measures. These limestones are of particular importance to this study as they form the karst terrain of the Takaka Valley floor. The limestones, outcropping throughout the Takaka Valley, mark the onset of a regional marine transgression in which most of the northwest Nelson area was submerged (Figure 2.2.f). (3) The Tarakohe Mudstone (Early – Middle Miocene) conformably rests on the limestone and consists of massive calcareous sandstone overlain by a massive calcareous mudstone (referred to locally as 'papa'). Correlated by Rattenbury et al. (1998) as Lower Blue Bottom Group, the terrigenous Tarakohe Mudstones reflect the renewal of tectonic compression and uplift and subsequent marine regression (Figure 2.2.g). Uplift on the Pikikiruna Fault during this period created the Pikikiruna fault scarp (Figure 2.4). The eroded eastern hanging wall (Pikikiruna Range) confines the Tertiary sequence within the study area to the Takaka Valley.

The Miocene stratigraphy is separated by a regional unconformity from the overlying Quaternary sediments (Thrasher 1989). The valley floor is predominantly covered in Quaternary alluvial terrace and flood plain gravel deposits with sinkhole development on the western side of the valley (Ravens 1990, Rattenbury et al. 1998).

2.3.3 Structure and Metamorphism

The Takaka terrane exhibits the earliest deformation event during the latter part of the Cambrian (Rattenbury et al. 1998). Shelley (1991) gives the age of the principal folds and deformations within the Arthur Marble as Silurian-Devonian (Figure 2.2 b). Shelley (1991) within Arthur Marble 2 records three phases of deformation, the first phase probably occurring when the sediment was incompletely lithified. All three phases are characterised by moderately inclined to recumbent folding. The major folds trend N-S to NNE-SSW and are reflected in the general strike of the range as seen on aerial photographs and in the mapping of Grindley (1971). The original mineral fabrics were almost completely overprinted during the second deformation phase, which coincides with the peak of metamorphism and NNW-SSE folds. The last Paleozoic deformation phase, as evidenced by calcite fabrics, caused widespread brecciation particularly towards the south and east of the study area (Shelley 1991).

The Paleozoic structures are interpreted by Shelley (1991, 1981) as an easterly verging tilted complex of thrust and nappes, and are collectively termed the Pikikiruna nappe. Shelley's interpretation contrasts with the mapping of Grindley (1971) which indicated west- and east-dipping surfaces delineating north-south upright folds.

Shelley (1991) reports that, as is common with thrust/nappe complexes elsewhere, the metamorphic gradients of the Pikikiruna nappe are inverted. The metamorphic grades within the Pikikiruna Range, while changing over short distances, are in general increasing in grade southwards and from low to high altitudes. Metamorphic mineral assemblages within the study area indicate metamorphic grades reaching upper greenschist to amphibolite facies (Rattenbury et al. 1998, Shelley, 1991, 1981, Cooper 1989).

As observed by several authors (Rattenbury et al. 1998, Shelley 1991), the intrusion of the Rameka Gabbro post-dates the deformation and metamorphism of the Arthur Marble, placing the timing of metamorphism in the Silurian-Devonian. Mineral assemblages from the Arthur Marble adjacent to later intrusions result from a secondary Mesozoic contact metamorphism (Sarll 1996, Shelley 1981).

The Pikikiruna Range is bounded on the western side by the Tertiary Pikikiruna Fault (Shelley 1991, Thrasher 1989). Evidence from the seismic reflection and well bore data indicate that the reverse motion on the Pikikiruna Fault is mostly constrained to the latest Miocene through Pliocene period (Thrasher 1989). Jongens (1992) in a structural study extends activity on the Pikikiruna Fault through to the Pleistocene. Ravens' (1990) seismic reflection survey interpretation of the structure in the Takaka valley and adjacent Pikikiruna Range indicates that faulting was most active until the Middle Miocene with a regional NNE compressional trend. Ravens (1990) also notes that no surface fault traces are observed in the Quaternary sediments. Shelley (1991) found that the Tertiary fault planes are parallel to the Paleozoic planes of deformation and may indicate reactivation of the older surface. The reverse faults are described by Shelley (1991) as east dipping structures that produced marked folding of the adjacent Tertiary strata (including the limestones) into near vertical attitudes, and raised the peneplain surface from below the Takaka Valley to above the Pikikiruna Range by approximately 1km. Uplift of the Pikikiruna Range may have been transferred from/to the Pisagh fault (Figure 2.4), which runs parallel to the Pikikiruna fault in an *en echelon* arrangement (Shelley 1991).

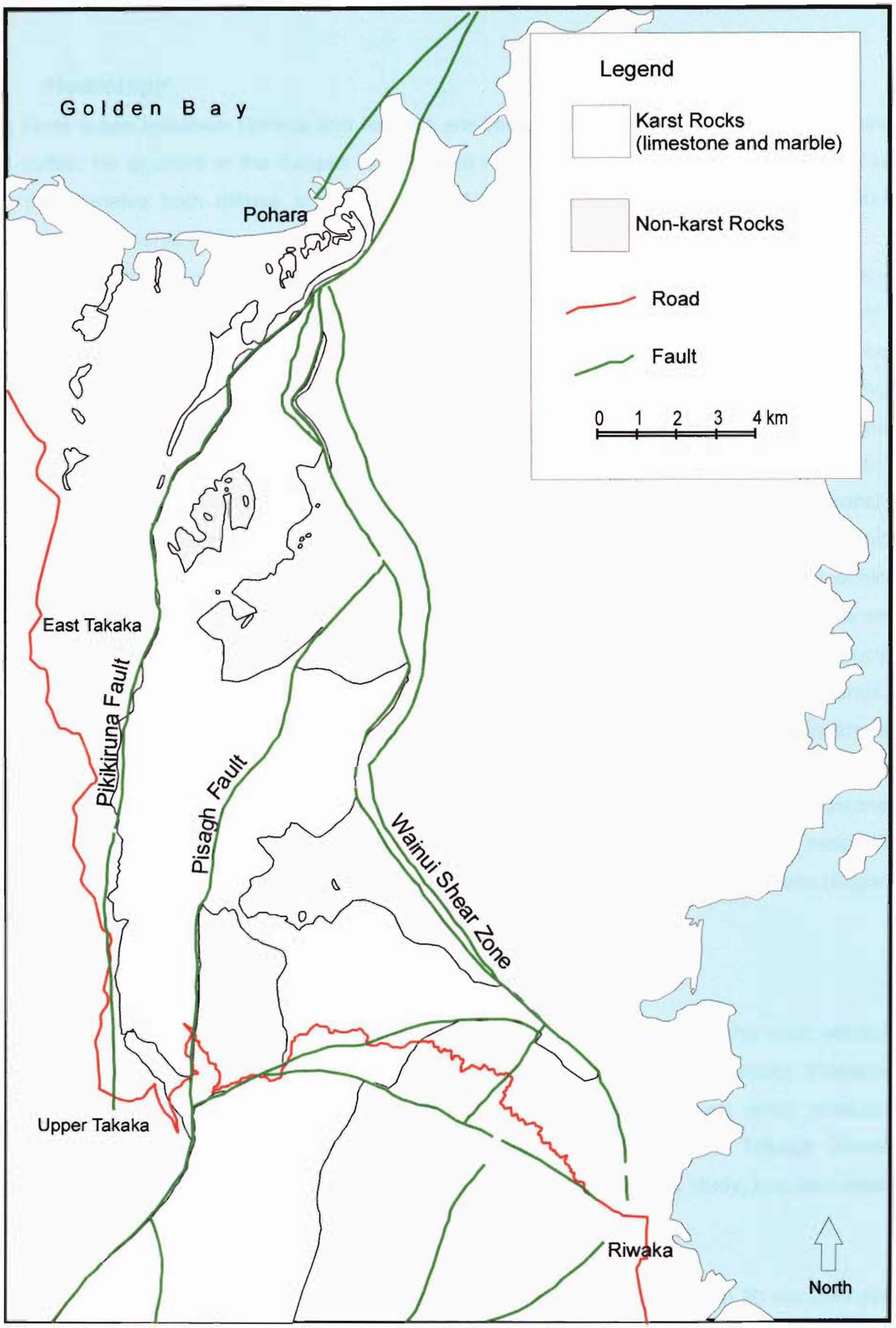


Figure 2.4. Faults influencing karst in the study area, northwest Nelson, New Zealand (Rattenbury et al. 1998)

2.4 Hydrology

The karst areas between Takaka and Riwaka are important catchments, storage reservoirs and outlets for aquifers in the Takaka and Riwaka regions. The aquifers are complicated in that they receive both diffuse and concentrated inputs derived from both autogenic and allogenic catchments (Edgar 1998).

Drainage boundaries in karst areas are often hard to define and aquifer characteristics vary widely. Internal catchment delineation within the karst areas is even less definite particularly, as the surface topography and hydrology often has little or no bearing on subsurface hydrological systems. For example, water tracing in the Takaka Walkway area by Dowling (1974) showed although to the east of the topographic divide and very close to Summit Cave, water sinking in Olympia Cave flows westward to the Takaka Valley (Figure 2.5). Waters sinking in Summit Cave drain east and resurge at the Riwaka North Branch Resurgence. To date, the dye tracing and subsequent study by Dowling (1974), and Williams and Dowling (1979) provides the best indication of potential drainage divides within the study area. Figure 2.5 illustrates the known hydrological connections within the area as defined by Williams and Dowling (1979). A prominent karst catchment boundary in the study area is that between the Takaka Hill Plateau area and the Canaan – East Takaka Uplands. The non-karst rocks of the Pikikiruna Range act as a barrier between the two recharge areas (Figure 2.5). In general, precipitation falling on the western side of the Pikikiruna Range provides recharge to the Waikoropupu Arthur Marble and East Takaka Motupipi Limestone aquifers of the Takaka Valley, while waters from the Takaka Hill catchments maintain supplies to the Riwaka River and other local waterways, such as Holyoake Stream (Edgar 1998, Williams 1992a, Williams and Dowling 1979).

2.4.1 Karst aquifer characteristics

The hydrology of the Takaka Valley is dominated by two karstic aquifers; the main aquifer being the Waikoropupu Arthur Marble (or WAM) aquifer with the East Takaka Motupipi Limestone (or ETML) comprising the minor aquifer (Figure 2.6). Two other shallow, unconfined gravel aquifers (the Takaka Township Gravel and the East Takaka Gravel aquifers) are located in the Takaka Valley and while not included in this study, are discussed in some detail by Edgar (1998).

The WAM aquifer, hosted by Ordovician Arthur Marble, and extending about 30 km from the head of the valley to the coast, is confined in the lower part of the Takaka Valley by overlying impervious sediments (Williams 1977). These aquicludes are comprised of units such as Motupipi Coal Measures and Tarakohe Mudstone (Mueller 1991). South of the East Takaka

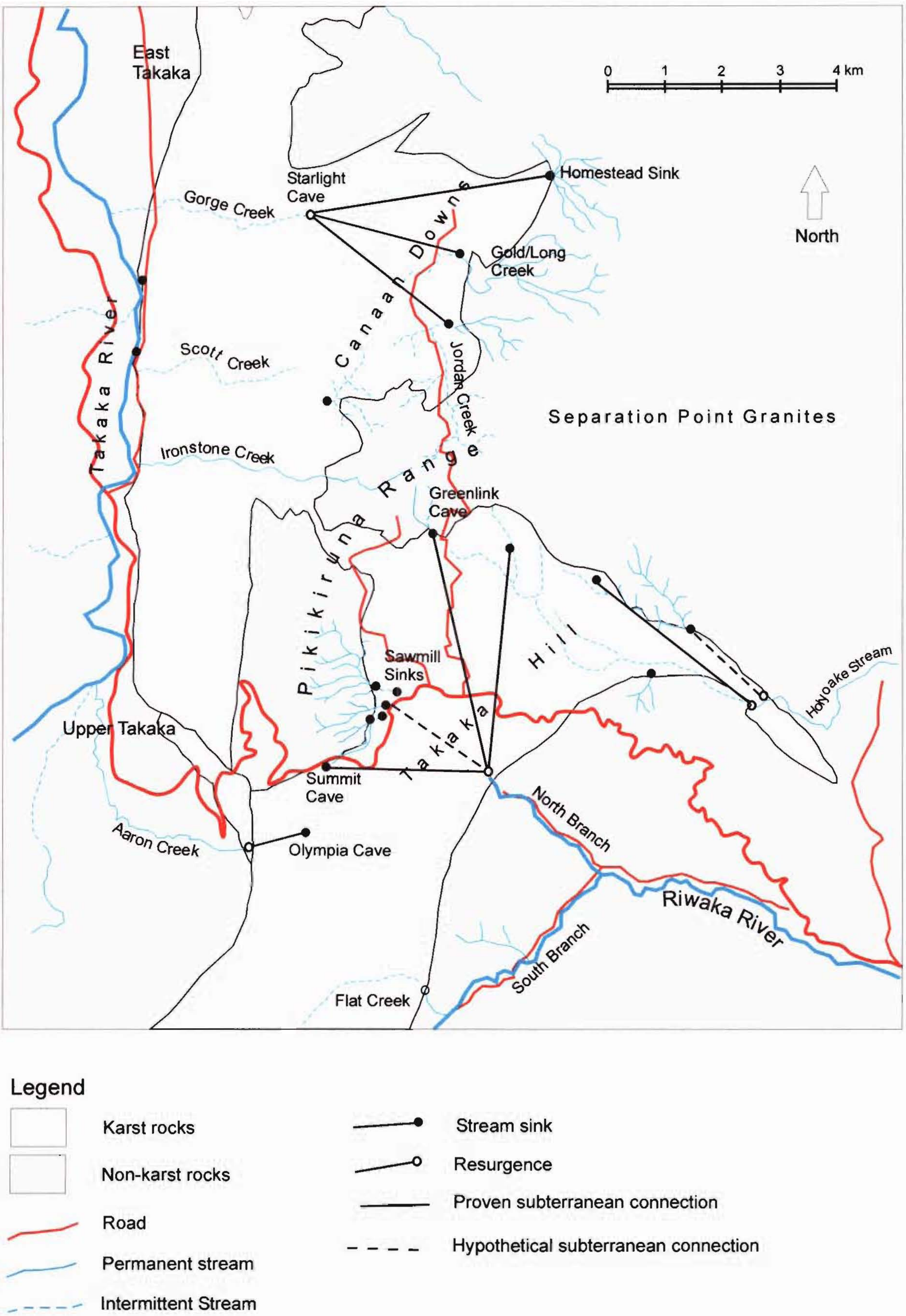


Figure 2.5. Results of dye-tracing of subterranean waterways showing known hydrological connections (Williams and Dowling 1979)

artesian boundary, the aquifer is unconfined and overlain only by thin permeable sediments (Williams 1977).

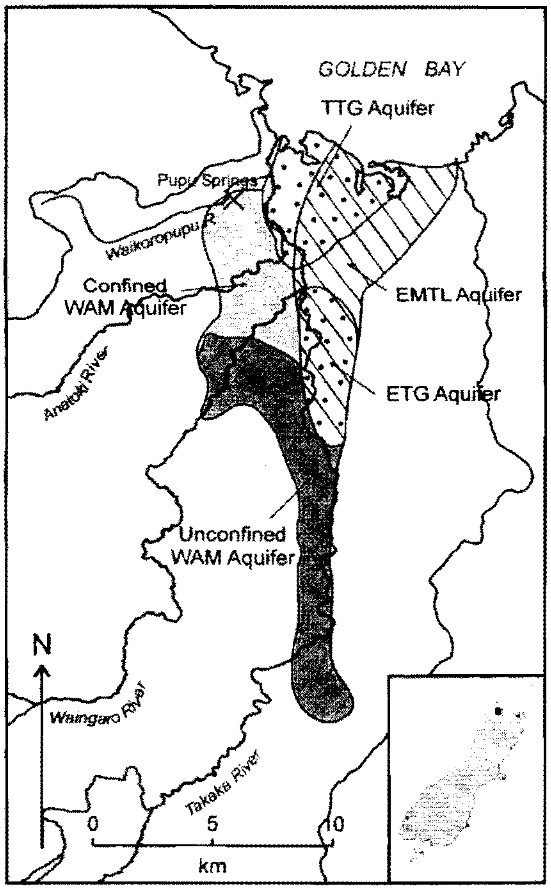


Figure 2.6. Takaka Valley aquifer system. (Edgar 1998)

Although Edgar (1998) detailed five separate recharge sources to the WAM aquifer, the main recharge inputs can be divided into three groups: Takaka River sinks, tributary river sinks and direct infiltration from rainfall. Williams (1977) was the first to provide evidence, using pulse train techniques, of the direct connection between losses in the Takaka River and recharge to the aquifer. Williams (1977) also estimated that approximately one third of the recharge to the aquifer is derived from Takaka River sinks, particularly those downstream of Lindsay's Bridge where the river passes close to outcropping marble at the foot of the Pikikiruna fault scarp. Further concentrated allogenic inputs are supplied to the aquifer from sinks located in rivers draining the western and eastern ranges. The main contributing rivers on the eastern side of the valley (within the study area) are the Waitui, Gorge and Rameka Creeks, and Ironstone Creek, which is the only waterway of the four to normally maintain flows throughout low flow conditions. Dry Creek, for example, only flows after 50mm of rain, this limit exceeded 15-20 times per year (Baird, J. *pers. comm.* 2003). Precipitation falling on outcropping or permeably covered karst rocks, particularly on the upland karst plateaus, comprises the autogenic recharge component (Edgar 1998).

Waikoropupu Springs (locally abbreviated to Pupu Springs), with an average discharge of 14 m^3/s (Williams 2001, Edgar 1998), are the primary outlets for WAM aquifer discharge. The karst waters emerging at Waikoropupu Springs take an average of approximately 3 to 8 years to travel through the system (Williams 1992a). Discharge also occurs at Spittal's Spring, where outflow has been directly linked to the Harwoods Hole - Starlight Cave - Gorge Creek system, and ephemerally at Springs Brook Spring (Williams, cited in Dowling 1979). Edgar (1998) discounts the presence of a significant outflow via the submarine springs located in Golden Bay. The flow has previously been estimated as 8 m^3/s by Mueller (1991) and Williams (1992).

Although minor, the East Takaka Motupipi Limestone aquifer is an important local supply of potable, horticultural and agricultural water. The ETML aquifer is subdivided into three sub-aquifers by Edgar (1998), namely the Clifton, Central Takaka-Motupipi and East Takaka sub-aquifers. A large component of recharge is derived via autogenic inputs to the aquifer, where rain falls directly on the limestone, and from infiltration of rainfall via the Pikikiruna Fault. Additional inputs are gained from Takaka River losses and infiltration through permeable gravels directly overlying the limestone. Waters flowing directly onto the limestone from the adjacent granites or via waterways such as Dry River and Rameka Creek provide concentrated allogenic inputs (Edgar 1998). Mixed allogenic and autogenic recharge to the combined aquifer may also be derived from inter-aquifer leakage.

In the Pohara area, where marble does not lie adjacent to the limestone, recharge is also provided by autogenic inputs. Allogenic inputs to the Pohara karst appear to comprise stream runoff from a small, unnamed streams which collect water from the slopes of the Pikikiruna Range. Many of the streams disappear into sinks, which are located on the back (southeast) of the narrow limestone ridge parallel to the Range.

Besides extraction from the 35 wells in the ETML, natural outflows are located at Motupipi and East Takaka Springs and from other smaller ephemeral springs (Edgar 1998). Two rising streams are located in the Pohara area, one of which supplies water to the TDC water reserve.

Runoff from adjacent non-karst rocks (Pikikiruna Schist, Riwaka Complex and Separation Point Granites) provides concentrated allogenic recharge to the Riwaka and Takaka Hill karst catchments. A distinct lack of surface waterways crossing onto the karst (apparent from looking at topographic maps or aerial photos) occurs because the allogenic streams disappear underground soon after reaching outcropping marble (Williams and Dowling 1979). Semi-concentrated autogenic recharge occurs on the Takaka Hill Plateau where the numerous dolines focus surface runoff. Diffuse autogenic recharge is derived from outcropping marble areas where there is little surface organisation of drainage (such as the Takaka Walkway), and the rainfall can rapidly infiltrate the subterranean systems.

Discharge sites include the Riwaka Resurgence, Holyoake Stream and Aaron Creek. The Riwaka Resurgence is a popular site for cave divers and has an annual average flow of 1m^3/s (Dowling 1974). Situated in a pocket valley or steephead in the Riwaka Valley floor, the picturesque Riwaka Resurgence is the source of the Riwaka North Branch River.

2.4.2 Throughflow and Storage

As the primary porosity of the Arthur Marble is very low relative to other rock types, the capacity of aquifers in this area to store and transmit water is controlled by characteristics such as fissuring or secondary permeability and thickness (Williams 1992a). Williams (1992a) notes that while flow rates in the Arthur Marble aquifers usually range from 0.5 – 1 m/day up to 300 m/day, areas with particularly high hydraulic head (such as the Pikikiruna Range) may generate flows velocities over 1 km/day. The flow-through times shown in Table 2.1, calculated from dye tracing experiments carried out by Dowling (1974) and Williams (cited in Dowling 1974) illustrate the speed at which water travels through karst systems. While some water flows rapidly through enlarged fissures and conduits, a significant amount of water is stored in the epikarst or subcutaneous zone (Williams 2001). This water which, is held in tight fissures and joints in the uppermost weather part of the rock just below the surface, provides slowly percolating water.

Stream Sink		**Resurgence**		**Travel***		**Max. flow through time (hrs)**
Name	Altitude (m)	Name	Altitude (m)	Horizontal (m)	Vertical (m)	
Greenlink Cave	747	Riwaka Nth. Branch	91	4260	655	72
Summit Cave	792			3050	701	22
Olympia Cave	890	Aaron Creek	305	1590	585	26
Homestead Creek	762	Starlight Cave/ Gorge Creek	183	4080	579	72
Gold Creek	777			2260	594	144
Jordan Creek	726			3100	543	72

* Travel distances given as straight line measurements.

Table 2.1. Results of subterranean water tracing. (Dowling 1974)

Although the thickness of the Arthur Marble has been estimated at over 1000m by Williams (1977), the depth to which effective permeable fissuring occurs and thus the depth of the aquifer may be, in some areas, as little as several hundred metres (Williams 1992a, Mueller 1991). The piezometric surface in the Arthur Marble aquifers is not constant nor homogeneous and the vadose-phreatic boundary may rise by tens of metres after heavy rainfall. The local base level in the WAM aquifer increases from the coast to Upper Takaka. The groundwater elevation in the marble ranges varies depending on local conduit patterns but in areas further from the coast the base level is, as evidenced by spring discharge elevations at the margins of the marble, several hundred metres above sea level (Dowling 1974).

2.4.3 Water quality

Waters derived from the karst aquifers of the Takaka Valley are utilised for agricultural, domestic and minor industrial supply. The groundwater must therefore be of adequate quality for drinking, irrigation and livestock (Edgar 1998). On-going water quality monitoring of the WAM (sampled at Pupu springs) and ETML (sampled at borehole WWD 6601) aquifers is undertaken three-monthly by TDC. Although waters discharging from WAM at Pupu Springs are very clear, the waters have a slightly brackish chemistry (elevated chloride, potassium and sodium) because of mixing with seawater (Mueller 1991, Williams 1977). Water quality is highly variable, being complicated by the differences and mixture of source waters and the variability in storage and discharge rates (Edgar 1998, Williams 1977). Results from water quality analysis of ETML waters indicate some degradation. The water is suitable for drinking, but moderately variable concentrations of nitrate and chloride are cause for concern (Edgar 1998).

Surface waters, such as the Takaka River and tributaries, providing groundwater recharge are also required to be of suitable quality to maintain, not only availability for direct consumption but also, biological and recreational values (Edgar 1998). It is perturbing to note that, as Edgar (1998) points out, based on New Zealand Drinking Water Standards, none of the water samples in the surface water sampling database would have been suitable for drinking without treatment. Results from the mid and lower Takaka River show the concentrations of nitrate and faecal coliforms are above the recommended guidelines (11.3 g/m3 and nil per 100 ml respectively). Edgar (1998) also observes that the elevated nitrate levels, which increase down the Takaka River (a peak value of 150 g/m3 was recorded at Paynes Ford, while the headwaters commonly register < 1 g/m3), correspond directly to land use.

Waters taken directly from the Riwaka karsts are largely used for irrigation of horticultural crops and agricultural supply. Potable water is drawn from the gravel aquifers of the Riwaka Valley. While the gravel aquifers retain some mark of the karst waters, the gravels provide some measure of filtering (Millar 2002). The waters derived from the karst catchments in this area are predominantly used for irrigation and agricultural supply. Detailed analyses of water quality for the Takaka Hill - Riwaka Resurgence have not yet been carried out. Monitoring of the Riwaka Resurgence (quarterly samples collected by TDC) has been on-going for 2 years and will provide the basis for groundwater quality assessments. A brief review of the available data shows that although the Riwaka Resurgence flows from a large spring, the waters are more representative of surface water samples taken in the area, with elevated nitrate levels and faecal coliform counts (Smith, R. *pers. comm.* 2002). These levels may reflect the rapid flow-through times as given in Table 2.1.

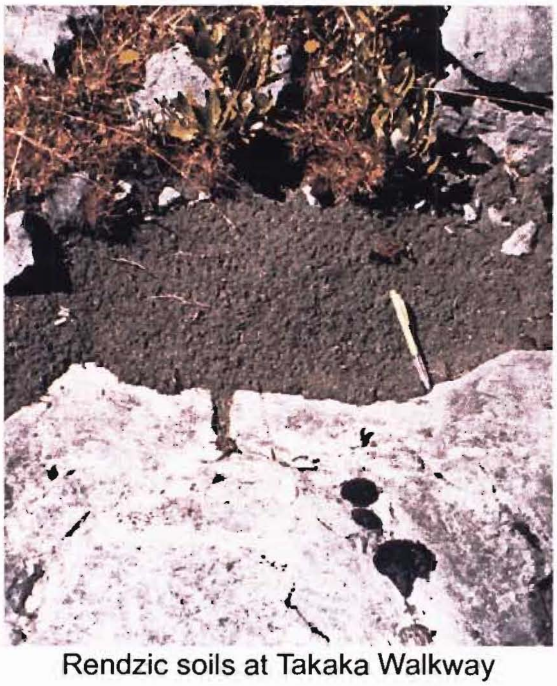
2.5 Soils

While soils are the products of local interactions between climate, rainfall, parent material, living organisms, topography and time, and so may vary considerably even over very small distances, the soils of the study area can be broadly differentiated into calcareous and non-calcareous soils. Calcareous soils are distinguished from soils formed on non-carbonate rocks because much of the rock is soluble and the soils formed from them are the residues remaining after solution processes have removed the balance of the rock. Many karst areas develop on quite pure carbonate rocks, with the proportion of insoluble material or non-carbonate residues commonly comprising less than 5% (Williams 1993). Thus, the soils are often thinner than in non-karst areas and are slower to form.

Most of the calcareous soils found in the study area are referred to as *rendzic* soils, a term used to denote calcareous and associated intergraded soils that have some non-carbonate derived material content or are not well developed. Well-formed soil profiles derived entirely from carbonate residues are known as *rendzinas* (Molloy 1993). The main soil types of the northwest Nelson area are indicated in maps by the New Zealand Soil Bureau (1968) and Gibbs (1980). The properties and characteristics of the calcareous and non-calcareous soils found within the study area are summarised in Figure 2.7.

The depth of the soil and/or sediment cover is a major differentiating factor throughout the area and varies considerably ranging from none to many metres. Soil thickness impacts on surface and subsurface landform expression and evolution, karst hydrology, and recharge systems. Soil thickness often corresponds to the distribution of rendzic soils in relation to non-carbonate soils. The thinner or often skeletal rendzic soils are associated with those areas that have been isolated from the input of material derived from neighbouring non-karst catchments. In contrast, relatively thicker non-calcareous soil profiles are found in areas in which the non-karst material is (a) *insitu* or in its original location or (b) distributed over the karst rocks by natural processes such as fluvial activity. Considerable deposits of alluvial sediments and non-calcareous soils in areas far removed from present day rivers and streams are commonly noted in the field.

Soil Type	Calcareous Soils; rendzic or rendzina soils and intergrades	Non-calcareous soils; Yellow-brown earths, brown granular soils, and recent soils
Colour	Black to dark brown, dark grey	Brown, yellow-grey, yellow-brown, tan
Structure	Strongly developed crumb, nutty or granular structure, often with no subsoil	Ranges from very friable well developed granular or crumb structure to very weakly developed blocky structures
Parent material	Limestone, marble, calcareous sandstone, mudstone	Granite, schist, mudstone and other non-calcareous rocks
Soils	Includes Pikikiruna, Kairuru, and Tarakohe Soils	Includes Rameka, Riwaka, Brooklyn, Haupiri, Pokororo and Ligar soils
General	Generally high nutrient status (low phosphate). Often directly overlying karst bedrock, no subsoil, commonly bouldery with many bare outcrops. Resistant to erosion due to high fertility and organic content, and good structure, although susceptible to being 'washed down' karst drainage features. Much of mapped rendzic soils include high proportions of rendzic intergrades to yellow brown earths.	Wide ranging soil properties, generally moderate natural nutrient status. Have simple soil horizons or topsoil-subsoil weathering layers, with more brown in topsoil and more yellow in subsoil. Yellow brown earths and brown granular soils require maintenance of vegetation to manage surface erosion, particularly on hills or steeplands. Recent soils are suitable for cultivation due to free drainage and good structure.



Rendzic soils at Takaka Walkway

Non-calcareous soils at Kairuru

Figure 2.7. Summary of calcareous and non-calcareous soils characteristics. (Molloy 1988, Gibbs 1980, New Zealand Soil Bureau 1968)

Soil type is an important control on the distribution of present and potential land uses. The non-calcareous soils in northwest Nelson are used for agriculture or, in lowland areas, horticulture. The rendzic soils are mainly suited to pastoral farming, with the lack of surface water and potential for drought a serious limitation to more intensive farming practices (Gibbs 1980).

2.6 Climate

The northwest Nelson region experiences a sunny, mild climate, and is less windy than most other areas (de Lisle and Kerr 1965).

Regionally the rainfall gradients decline from west to east. Locally, the weather is strongly affected by aspect and altitude, which markedly influence mean temperatures and rainfall. Mean annual rainfall is predominantly controlled by altitude (Table 2.2). More frequent rainfall may be expected on the higher altitude areas such as the Pikikiruna Range and Takaka Hill. Heavy rainfalls, which sometimes occur especially on the western side and northerly exposed areas of the study area, are largely controlled by orographic precipitation derived from the prevailing westerly and northerly winds (Doyle, M. *pers. comm.* 2002). These changes are observed in comparisons of the measured climatic factors and observed changes in vegetation throughout the study area (de Lisle and Kerr 1965). The normalised rainfall means for the north-west Nelson area are illustrated in Figure 2.8.

Rainfall Station	Elevation** (metres above sea level)	Rainfall normals (per year)
Motueka	10	1263 mm
Tarakohe	<10	1533 mm
Riwaka Valley	100	1775 mm
Takaka	40	1838 mm
Kairuru	520	2313 mm
Takaka Hill	900	2138 mm
Canaan*	800	3878 mm

* Canaan rainfall mean taken from 1994 – 2002 (Tasman District Council)
**.Altitudes taken from topographic maps

Table 2.2. Annual rainfall normals for 1951 – 1980 (New Zealand Meteorological Service).

Although spread evenly throughout the year, rainfall figures do show a slight increase in the winter months from May to October. Table 2.2 gives the mean annual rainfalls levels for the area and illustrates the difference in rainfall between the western and eastern, and elevated areas. Much of the area is prone to frequent frosts in winter, with the exception of protected

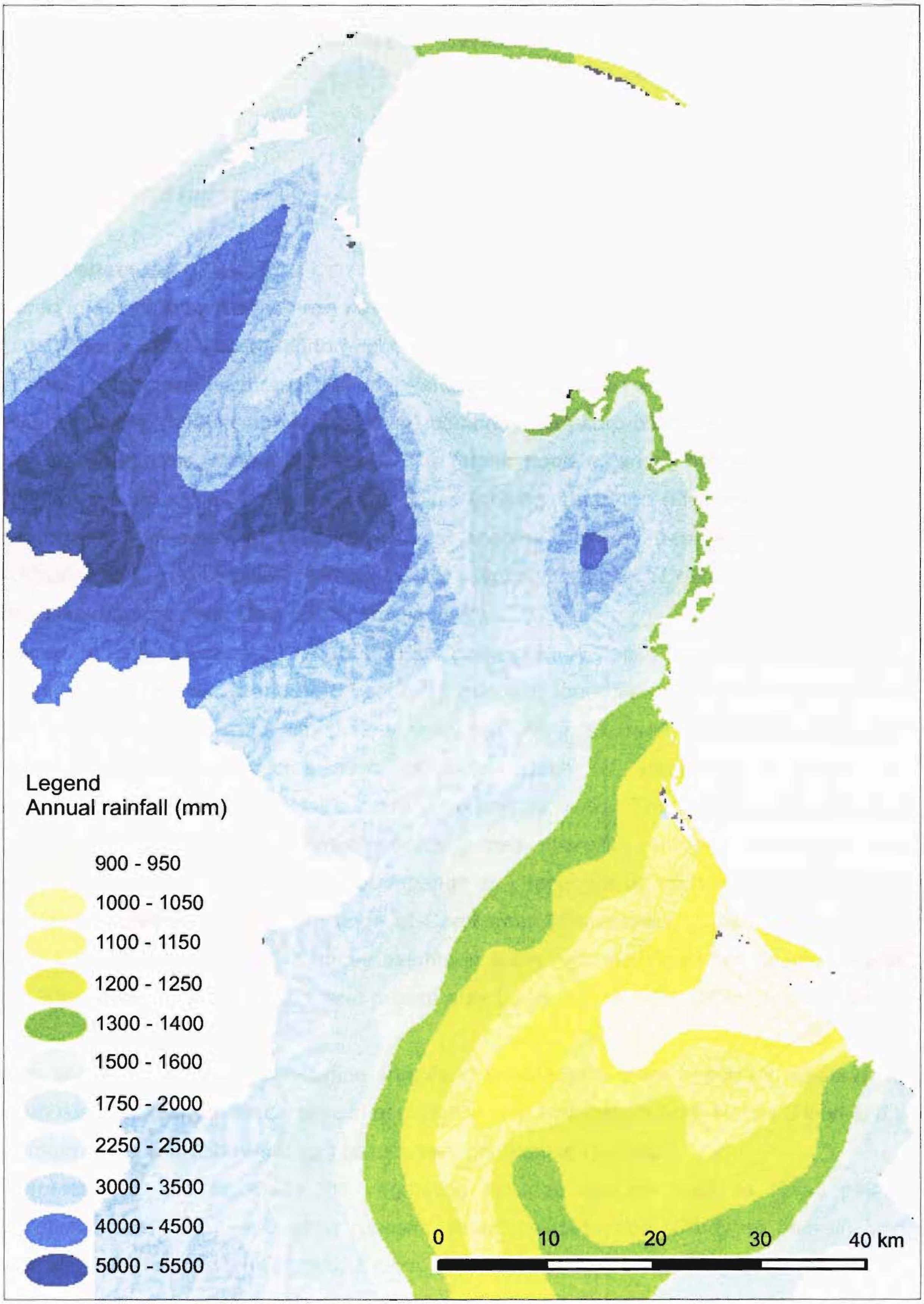


Figure 2.8. Areal isohyetal rainfall distribution map, showing annual rainfall for northwest Nelson. Rainfall gradients decrease from west to east. (Modified from Tasman District Council, 2002. Reprinted with permission)

coastal areas such as Clifton and Motupipi. Several snowfalls per year are encountered on the upper exposed ranges.

2.7 Flora and fauna

2.7.1 Vegetation

Prior to forest disturbance the area was covered with stratified native forests, remnant stands of such forests remain scattered throughout the area today with significant cover remaining in the Abel Tasman and Kahurangi National Parks and other reserves.

Lowland forests (<600m above sea level) comprise podocarp-broadleaf tree species with some beech species (*Nothofagus spp.*). The forests contain canopy tree taxa such as rimu (*Dacrydium cupressinum*), matai (*Prumnopitys taxifola*), and miro (*Prumnopitys ferruginea*) and include a diversity of secondary forest species such as tree ferns (*Cyathea sp., Dicksonia sp.*), nikau palms (*Rhopalostylis sapida)*, akeake (*Dodonea viscose*), rata (*Metrosideros spp.)*, and tawa (*Beilschmidia tawa*).

Montane forests (between 600 – 1000m) are dominated by beech trees (*Nothofagus spp.*), with red beech (*N. fusca*) and hard beech (*N. truncata*) found in areas with better soils and more favoured sites. Areas with skeletal soils, or those in exposed conditions host stunted forests dominated by species such as silver beech (*N. menziesii*), southern rata (*Metrosideros umbellate*) and Hall's totara (*Podocarpus hallii*). The montane beech forests maintain an understorey of broadleaf (*Griselinea littoralis*), horopito or pepper tree (*Pseudowintera sp.)*, lancewood (*Pseudopanax sp.*), lacebark or houhere (*Hoheria ovata*), tree daisys (*Olearia spp.*) and a range of Coprosmas (Shulmeister, J. *pers. comm.* 2003, Millar, I. *pers. comm.* 2002). Canopy heights in areas with significant soil depths may be over 20m, whereas the stunted forest growth may be as low as 2-3m (Millar, I. *pers. comm.* 2002).

Areas above 1000 m with sub-alpine shrubland taxa include silver beech (*N. solandri var cliffortioides*), and *phyllocladus spp.* in association with *Halocarpus spp.*, Hebes (*Hebe spp.*). Mountain neinei (*dracophyllum sp.*) occupy very dry exposed ridges.

In protected or coastal areas the vegetation includes species such as Nikau palms, *Macropiper excelcius*, *Geniostoma rupestre*, forest cabbage tree (*Cordyline banksii*), and mountain flax (*Linum sp.*) (Richards, J. *pers. comm.* 2002).

Much of the terrain outside of inaccessible or protected areas has been modified and now supports improved pastures and/or regenerating shrublands, and to a lesser extent plantation forestry mostly comprising *Pinus radiata* (Millar, I. *pers. comm.* 2002). Bracken (*Pteridium sp.*) and gorse (*Ulex europaeus*), regenerating natives such as Coprosmas, akeake, and unpalatable plant species such as pepper tree and totara occur where the land is idle or stock numbers are low. Dense stands of manuka and kanuka (*Leptospermum spp.*) can be found on previously cleared sites and appear to be more commonly associated with non-calcareous soils.

Much of the area sustains calcicole plant species that are especially adapted to the limestone-dominated conditions. Calcicole plants in the area include *Melicytus obovatus, Pimelea lingifolia,* northwest Nelson tree daisy (*Brachyglottis hectori),* and *Sophora longicarinata,* a kowhai species endemic to Nelson/Marlbourough (Millar, I. *pers. comm.* 2002, Richards, J. *pers. comm.* 2002).

2.7.2 Cave Fauna

Cave dwelling species such as glowworms and wetas are widely distributed throughout karst areas of New Zealand. Cave dwelling or *troglobitic* fauna is commonly divided into three main groups; troglophiles, trogloxenes, and troglobites. Glowworms belong to the *troglophile* group, those species that are adapted to living in caves but can survive in similarly dark, damp, above-ground habitats. Wetas are considered as *trogloxenes*, those organisms which prefer underground environments but which require surface environments at some time. The last of the groups, and those which generally attract the most scientific investigation, *troglobites* are those fauna which are entirely restricted to subterranean habitats. Troglobites characteristically have features, such as absent or reduced vision, long sensory hairs and little or no pigment, which are specific to survival in 'deep', stable cave environments or those caves which are isolated from exposure to surface conditions (Millar, I. *pers. comm.* 2002).

Compared to other karst regions in New Zealand, the extensive karst terrains of north-west Nelson support the greatest diversity of troglobitic taxa. Council Cave, located in the limestone, has been identified by Worthy (1990) as nationally significant for its troglobitic fauna. Species diversity is high within the study area due to the high number of separate or unconnected karst areas (Millar, I. *pers. comm.* 2002). Troglobitic species found in the study area include at least five species of ground (*Carobid*) beetles, at least three species of harvestmen (*Opiliones*), several unclassified species of millipedes and centipedes (*Myriapods*), and numerous aquatic taxa, such as crustaceans and snails (*Hydrobiidae*).

A review of troglobitic fauna by Millar (*pers. comm.* 2002) shows that many species are only found in discrete areas of the karst. For example, the rare and endangered Nelson Cave Spider (*Spelungula cavernicola*) is only known in two limestone caves in Golden Bay (Millar 1997). New Zealand's only troglobitic cixiid bug (*Confuga persephone*), which feeds on subsurface tree roots is also endemic to the limestones.

Millar (*pers. comm.* 2002) does note however, that the distribution of cave fauna in the study area may in part reflect inconsistencies in the search for and collection of, or accessibility of the cave dwelling species. Once explored, previously unsearched areas or new caves often provide a diversity of cave fauna. A lack of accessible taxonomic information also limits the knowledge of individual cave faunal species.

2.8 Local History and Land use

Although Golden Bay and Abel Tasman National Park have long been home to Maori people, Maori settlement on karst areas was limited because of the *rahui* emplaced on karst areas by local iwi (Manawhenua Ki Mohua Iwi, *pers. comm.* 2003). Likened to a trespass notice, a rahui is considered as an embargo on entry to a specific, often spiritual area. Karst, as does all other land, is believed to represent Papatuanuku, the Earth Mother and the karst topography and caves, in particular, are thought to be where the world and universe come together (Department of Conservation 1999). Although written information regarding karst and Maori in northwest Nelson is scarce, several sources relate that the karst was associated with the presence of a spiritual entity or taipo (or goblin) which was said to reside in the Canaan area (Sixtus 1993). Charles Heaphy, who crossed the Takaka Hill in 1843 was asked by Maori residents on the coast if he had encountered the Taipo. Maori people travelling from Golden Bay to Tasman Bay went via the coastal areas so as to avoid the karst on the Takaka Hill.

The karst was not avoided entirely, and there are numerous local accounts of alleged burials in the karst tomos or shafts, particularly in the limestone areas near Tarakohe and Pohara.

The karst landscape did not deter European travellers and residents. Gold and moa-bone prospecting led explorers into other karst areas, a bridle track was formed from Rameka to the natural clearing at Canaan in 1898 (Sixtus 1993). Gold was first located in Long Creek, Canaan in 1917 (Sixtus 1993), limited gold sluicing commenced and remains of the workings are visible today. Also present today, is a stalagtite in Ngarua Caves bearing the dated autograph (1876) of an early surveyor, H. Everett.

Vegetation clearance for farmland development first commenced around 1900, somewhat later than other areas in New Zealand. Kairuru, on the eastern side of the Takaka Hill, was cleared around this time (Henderson 1983). The bush was first felled in Canaan about 1919 (Sixtus 1993) and a review of the Canaan Downs area today reveals that the extent of the Canaan farmland was limited to karst areas with relatively thicker soil profiles or more fertile rendzic soils. The original bush was felled by axe (often single men working alone) and then left for a period for the wood to 'dry off'. The felled bush was then fired and grass seed, hand collected from local roadsides, applied to the charred areas. Accounts of the tree felling state that the felled forest often had to be re-burnt or logged out as it lay so thick on the ground (Sixtus 1993).

The last widespread forest clearances occurred in the late 1970's when beech forest on predominantly non-karst areas adjacent to the karst terrain was felled for wood chipping. Some plantation forest blocks (*Pinus sp.*) occur on the upland areas with the majority of the blocks occurring on the East Takaka - Pikikiruna fault escarpment, where a relatively small allotment was recently harvested.

Limestone extraction at the Tarakohe Quarry commenced around 1910 and continued until closure in 1988. Crushed and kiln processed, the limestone, and associated marl, provided material for cement production. At peak production, during the mid-late 1970's the quarry employed around 300 persons and processed 300 000 t per year of material (Smith, J. *pers. comm.* 2003). The Tarakohe quarry and cement works remain as a prominent local landmark.

Economic quarrying of the marble was first carried out for a short period at the Kairuru Quarry (1911 - 1912), where very pure, white marble was mined and transported to Wellington for use in building parliament (Watson, R. *pers. comm.* 2002). Limited quarrying of whole marble slabs (1960's) has caused some removal of the flat-lying limestone pavement located at the Marble Acre Quarry, Canaan (McKay, N. *pers. comm.* 2003). Presently, quarrying within the study area is limited to Ngarua where the 98% pure calcium carbonate is refined for use as agricultural fertiliser, or for use in chemical processing industries including paper processing. Quarrying of Ngarua marble commenced in the mid 1930's. Production figures for the present time are around 20 000 t per annum (McKay, N. *pers. comm.* 2003).

On a much lesser scale and for more aesthetic purposes, large, well-sculpted ornamental blocks were (and are) removed, often locally, for use in landscaping. Although now prohibited, rock continues to be stolen from the Takaka Hill area (Nelson Evening Mail, April 2003).

Today the cleared upland areas predominantly support improved pastures for sheep, cattle and goat grazing. Many farmed areas are, increasingly, being subdivided for lifestyle farm blocks. The farm blocks often retain their original agricultural function although some are regenerating to natives or are in the intervening stages of gorse and bracken colonisation. The upsurge in lifestyle farming is reflected in increases to the population. Census figures from 1991 to 2001 for the Takaka Hill show that the population has grown from 105 to 225 persons (Statistics New Zealand, Crown Copyright).

Karst land in the lowland or valley areas is predominantly utilised for agriculture. The land (with more available water) is more suited to intensive farming such as dairy grazing and horticulture than the karstic uplands. The favourable climatic conditions found in the lee of the Motupipi - Clifton limestone ridge has led to the development of several small orchards and market gardens. The regional trend in population growth, and urban migration to rural and coastal locations, is also seen in the development of residential sections in the valley, particularly near the coast. Population data for the Pohara area, where most residential development has occurred, show that the 1991 population of 429 has increased to 594 in 2001 (Statistics New Zealand, Crown Copyright.).

CHAPTER THREE – METHODOLOGY

3.1 Introduction

This chapter outlines the field and laboratory procedures used to obtain information.
An understanding of karst landforms and terminology is integral to this research, and field recognition of the karst landforms was required during the early stages of mapping. Therefore, some information regarding the significance of karst landforms or associated features present in the study area and evaluated during the geomorphological classification and lithological sampling is presented in this chapter.

3.2 Geomorphological mapping

Geomorphological mapping was carried out over an eight-week period in the summer of 2001-2002. Preparatory and working procedures followed standard mapping schemes (Cooke and Doornkamp 1990, Demek et al. 1972). The preparatory collation of background data included information from sources such as geological, topographical, and soil distribution maps, cave and karst inventories and aerial photographs. An initial reconnaissance field mapping period was undertaken.
Landowners were contacted to gain permission to enter property and to gather anecdotal information on the karst systems.
The boundaries of the field area were defined after the reconnaissance field inspection, during which a working (or draft) land systems map was prepared. Land system mapping is generally used to classify land and/or resources for land use and resource planning (Gunn and Nix 1977). The concept of land systems mapping is applied in this study to define mappable and easily identifiable karst landform units. The land systems map delineated karst units, or zones, where a similar pattern and/or distribution of topography, drainage, karst landforms and soils were located.
Colour aerial photographs, originally produced at 1:50 000 scale at and enlarged to 1:7500 scale, were used in conjunction with overlays to provide base maps for the field mapping. The 1:7500 scale allowed each photograph to be printed on AO size pages and was determined to be the optimum scale to identify and map karst landform features and their local distribution while allowing for the filtering of unnecessary detail. Individual karst landforms and associated features smaller than approximately 2m diameter were not mapped. The geomorphological mapping involved traverses at a varying scale with relatively denser traverse distances occurring in areas of higher landform density.

Areas of heavy forest cover or extreme topographic relief were mapped from stereographic photograph interpretation and the 1:50 000 Takaka and Tarakohe topographic maps (Department of Lands and Survey 1986, 1984). Smaller sections of inaccessible areas were field proofed to ensure that mapping results were not biased towards areas of easier access, which are predominantly modified by human activities. The Tarakohe area of the Pohara karst zone was precluded from mapping because of restricted access. The mapping coverage is illustrated in Map 1.

Landforms identified in the field were cartographically represented on the base maps using geomorphological mapping symbols and notations (after Demek et al. 1972). Slope classes shaded according to slope angle and lithology represent the base of the maps. The slope classes, derived from map contours are taken from the suggested International Geographical Union (Demek et al. 1972) classes, ie. 0–5°, 5–15°, 15-35°, >35°. The lowest and highest classes were modified in response to the lack of low angle slopes and the limited extent of high angle regions within the project area.

3.3 Geomorphological and lithological sampling sites

Collected to confirm and quantify observations made during the mapping, geomorphological and lithological data also assisted in identifying processes that influence the distribution of landforms in the karst zones.

Lithological samples and geomorphological classifications were taken, where possible, at the same location.

Random stratified sampling was applied throughout the karst zones. Eight overlays, prepared using a 9 x 9 grid in which at least 30 of the quadrants were marked, were used in conjunction with the 1:7500 scale base maps to identify the sample sites. The grid quadrants were selected using random numbers (Quinn 1974). In the field, the sample sites were defined using an arbitrarily chosen 10 m radius. For data recording, sample sites were GPS located using the New Zealand map grid system.

The lithological and geomorphological classification sampling sites are given in Figure 3.1. The sample sites were restricted to those areas of the karst zones covered by the detailed geomorphological mapping. Some grid points, particularly in the Takaka Walkway and East Takaka karst zones were rejected for access or safety reasons. Alternative sampling sites were located as close as possible to the original site. The Marble Acre karst pavement, considered too small for inclusion as a karst zone, was not included in the sampling programmes.

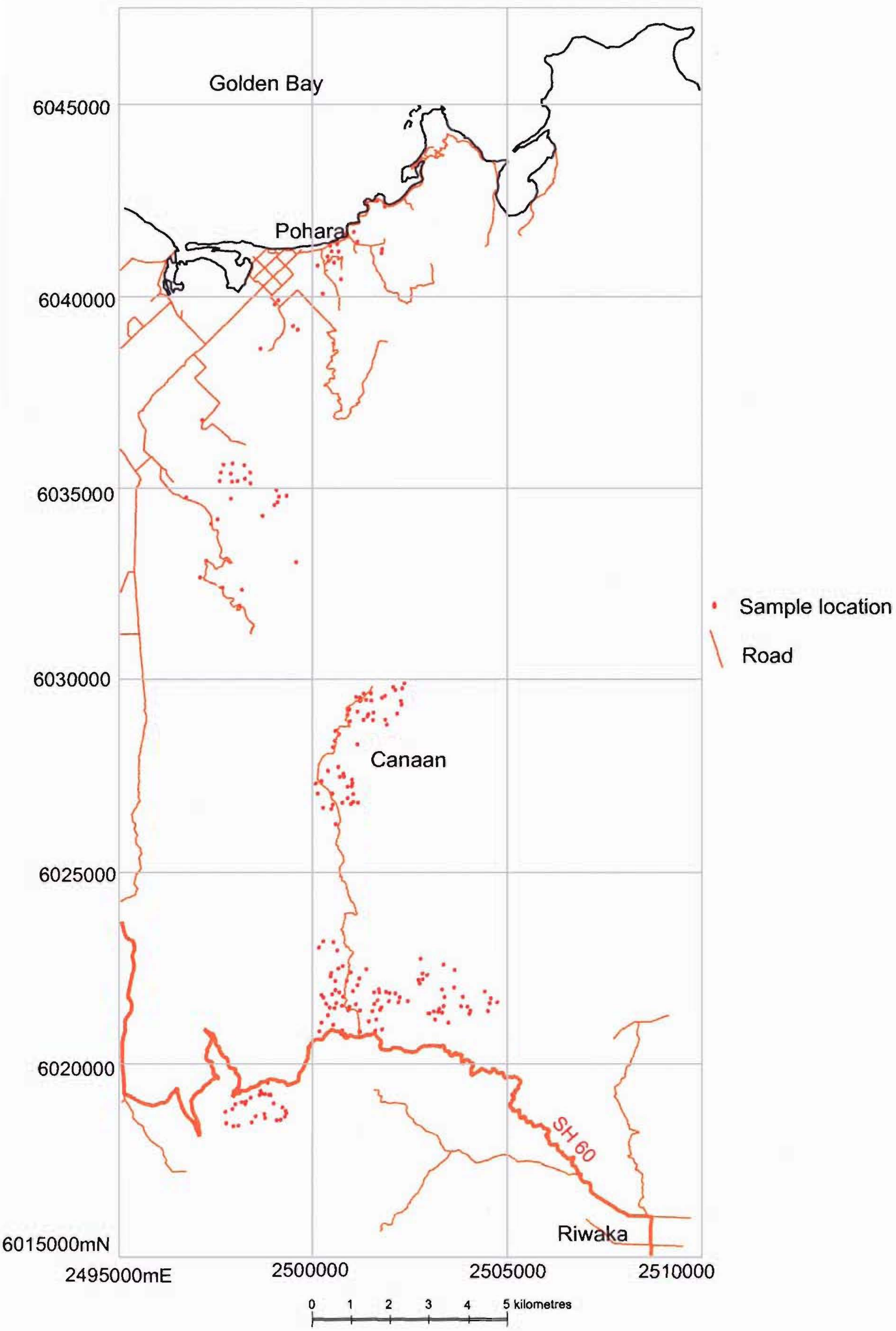


Figure 3.1. *Location of geomorphological classification and lithological samples.*

3.4 Geomorphological Classification

The geomorphological classification scheme was compiled by reviewing and synthesising morphological components of the karst literature (Ford and Williams 1989, Trudgill 1985, Sweeting 1981, 1973, Bogli 1980, Jennings 1971).

The geomorphological classification occurred over a three-week period in June 2002. The classification programme comprised a detailed look at approximately 30 randomly selected sample sites within each landform assemblage zone, with the exception of East Takaka where access constrained sampling (19 samples). Developed to assist in the consistent collection of geomorphological information, a sample geomorphological classification form is given in Figure 3.2. The information collected comprised topography, the dip, strike and frequency of structural discontinuities (fracture frequency), vegetation type, soil cover, the dominant drainage type, and the type and characteristics of karst landforms present. The type of features noted included karst valleys, hydrological features (such as springs and sinks), dolines, and karren.

Categorical data comprising the type and frequency of dolines and karren in each karst zone was collected.

3.4.1 Karst valley evaluation and identification

Karst valleys, which are predominantly subsurface equivalents of surface, non-karst drainage systems, includes features such as through valleys, dry valleys, blind valleys, poljes, pocket valleys, and stream sinks (Trudgill 1985, Sweeting 1973). Karst valleys often represent the first stage of karstification, or reorganisation, of the surface waterways into underground systems (Trudgill 1985) and thus, were useful for evaluating the history of karstification. The valley forms, are usually associated with surface flows (allogenic drainage) and are therefore, formed by a combination of fluvial and karst processes (Bogli 1980, Sweeting 1973).

The principal features used in the field recognition and evaluation of karst valleys included the presence of alluvial, fluvial and paleo-fluvial deposits, linear and centripetal valley slopes, and disappearing or resurging waters. Fluviokarst landforms are illustrated in Figure 3.3.

Through (or allogenic) valleys occur when rivers crossing the karst have sufficient volume to maintain flows across the surface to the output boundary (Ford and Williams 1989, Sweeting 1973). Gorges or valleys, incised by the flowing waters are characteristically narrow and steep sided. Antecedent-through valleys or gorges (after Ford and Williams 1989) develop where surface flows can incise at a rate greater than tectonic uplift.

Karst Geomorphology Classification Sheet

Location: ______________________ Date: ______________________
Karst Zone: ______________________ Sample No(s): ______________________
Northing/Easting: ______________________ Photograph No(s): ______________________

Sketch map available for kast geomorphology, doline or karren detail or additional notes:

Karst:

Dip/strike of bedding: __________ Slope gradient: __________
Hardness: __________ aspect: __________
Fracture Frequency (per unit): Current vegetation type: __________

1	4	7
2	5	8
3	6	9

Dip of structure (NB. jt, ft, fr, di): Deforested: __________

1	4	7
2	5	8
3	6	9

Doline/sinkhole type:

Solutional ☐
Alluvial ☐
Collapse ☐
Subsidence ☐
Uvala ☐
Undetermined ☐
comment (include impact if applicable):

Doline morphology

Symmetrical ☐
Assymmetrical ☐
Irregular ☐
Average size: __________
Strike of long axis __________
nature of sediment or vegetation cover:

associated landforms:

Karren type:

		Average size (depth/length)	Horizontal/ inclined surface	Other
Rillenkarren	☐			
Trittkarren	☐			
Rinnenkarren	☐			
Meanderkarren	☐			
Spitzkarren	☐			
Rundkarren	☐			
Solution basins	☐			
Grikes/clints	☐			
Pavement	☐			

Comment (include impact if applicable):

Macro landform description (ie. Blind valley, dry valley, sink, resurgance, cave entrance, impact):

Figure 3.2. Sample geomorphology classification form.

Blind valleys occur when rivers or streams flowing on the karst become absorbed at their lower end via the development of vertical drainage (Ford and Williams 1989, Trudgill 1985). The downstream channel of the stream will then be dry. In well-developed karst systems, all allogenic drainage entering the karst is engulfed at a stream sink soon after reaching the carbonate rock contact (Sweeting 1973). Valleys, in which water flows past the normal point of disappearance during high flow conditions are termed semi-blind valleys (Trudgill 1985). Blind valleys are often marked at the point of stream absorption by a headwall or cliff. Blind valleys, in response to concentrated drainage and thus, focused solution, are often marked at the point of disappearance by a cave (Sweeting 1973).

The former downstream channel, left abandoned by stream engulfment in a blind valley is termed a dry valley (Trudgill 1985). Sweeting (1973), notes that the nature of the carbonate rocks influences the morphology of karst valleys, with steep-sided forms occurring in thicker, massive carbonate sequences. U-shaped or gentle-sided valleys do occur and are more commonly older than narrower valleys. Dry valleys are regarded as one of the most widespread valley forms and commonly occur in response to the lowering and karstification of previously overlying, non-karst drainage networks (Sweeting 1973).

Pocket valleys (or steepheads, after Jennings 1971) are discerned by a headwall or cliff at the head of stream resurgences and are the opposite of a blind valley (Sweeting 1973).

Poljes occur as closed basins with steeply rising marginal sides, a flat valley floor covered in alluvium, and karstic drainage (Gams 1978, cited in Ford and Williams 1989).

The point of stream disappearance is referred to as a sink. Sweeting (1973) distinguishes sinks with little topographical expression from those forming significant relief. Streams associated with inconspicuous sinks lose flow gradually and do not feature an incised point of engulfment. Over time the fissures absorbing the stream flows are enlarged and distinct sink holes are corroded into the streambed. The location of the stream sink will eventually migrate upstream, abandoning the downstream sinks. Sinks with topographic expression are commonly related to caves or vertically sloping entrance shafts.

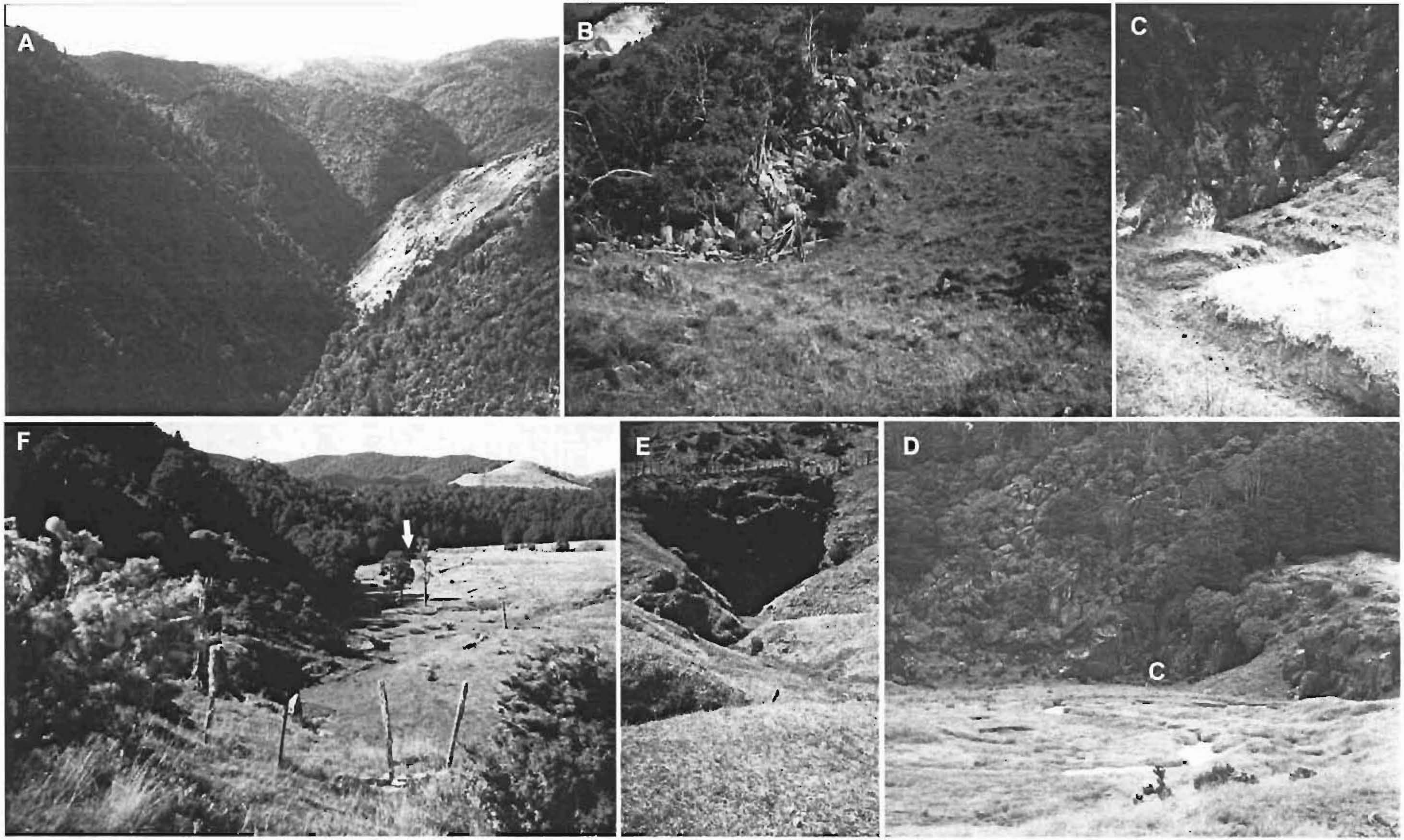


Figure 3.3. Karst Valleys. (clockwise from top left) A. Karst gorge (East Takaka) B. Blind valley, note debris at point of entry at bedrock exposure (Kairuru) C. Sink at end of blind valley, location marked on plate 'D' (Canaan South) D. Main sink area, blind valley with headwall development. Stream channels visible in the photo are dry (Canaan South) E. Small blind valley (Canaan South) F. Semi-blind valley developing due to headward stream migration. The stream gradually sinks in gravels at the point marked with an arrow

3.4.2 Doline evaluation and identification

The presence of dolines indicates the establishment of vertical drainage networks (Ford and Williams 1989). Dolines or sinkholes, as they are referred to locally, are enclosed depressions of small to moderate dimensions (Sweeting 1973) and are the most widespread karst feature. The term sinkhole is avoided in this study to prevent confusion with stream sinks.

The identification of dolines relies on determining solution or collapse as the primary mode of development. This genetic distinction identifies three main doline classes (after Ford and Williams 1989), solution, collapse and alluvial (or suffosion) dolines (Figure 3.4). Determination of doline genesis was particularly useful in assessing the predominance of different landforming processes.

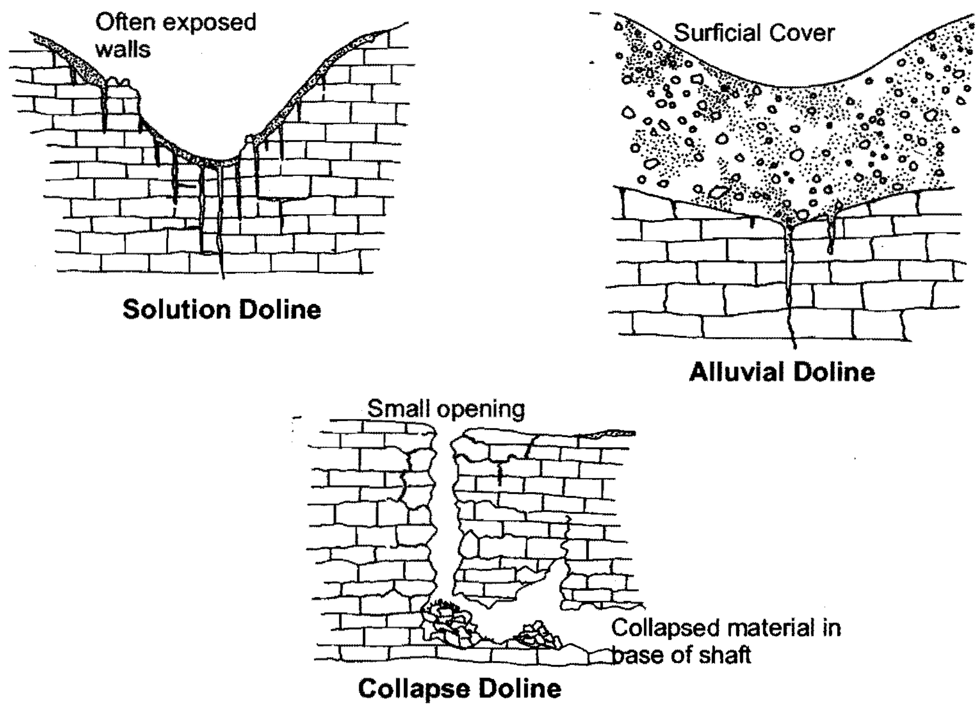


Figure 3.4. main genetic classes of dolines (adapted from Williams 1969).

Dolines in the study area are illustrated in Figure 3.5. Solution dolines develop because enlargement of underlying fractures by dissolution focuses corrosion and the surface is subsequently lowered (Sweeting 1973). Alluvial dolines (or suffosion dolines) are found in areas where alluvium or other sediments cover the karst bedrock (Figure 3.5). Corrosion of the bedrock underneath the cover creates piping along enlarged joints and fractures allowing the sediment to subside into the openings by a combination of solution and downwashing (Ford and Williams 1989).

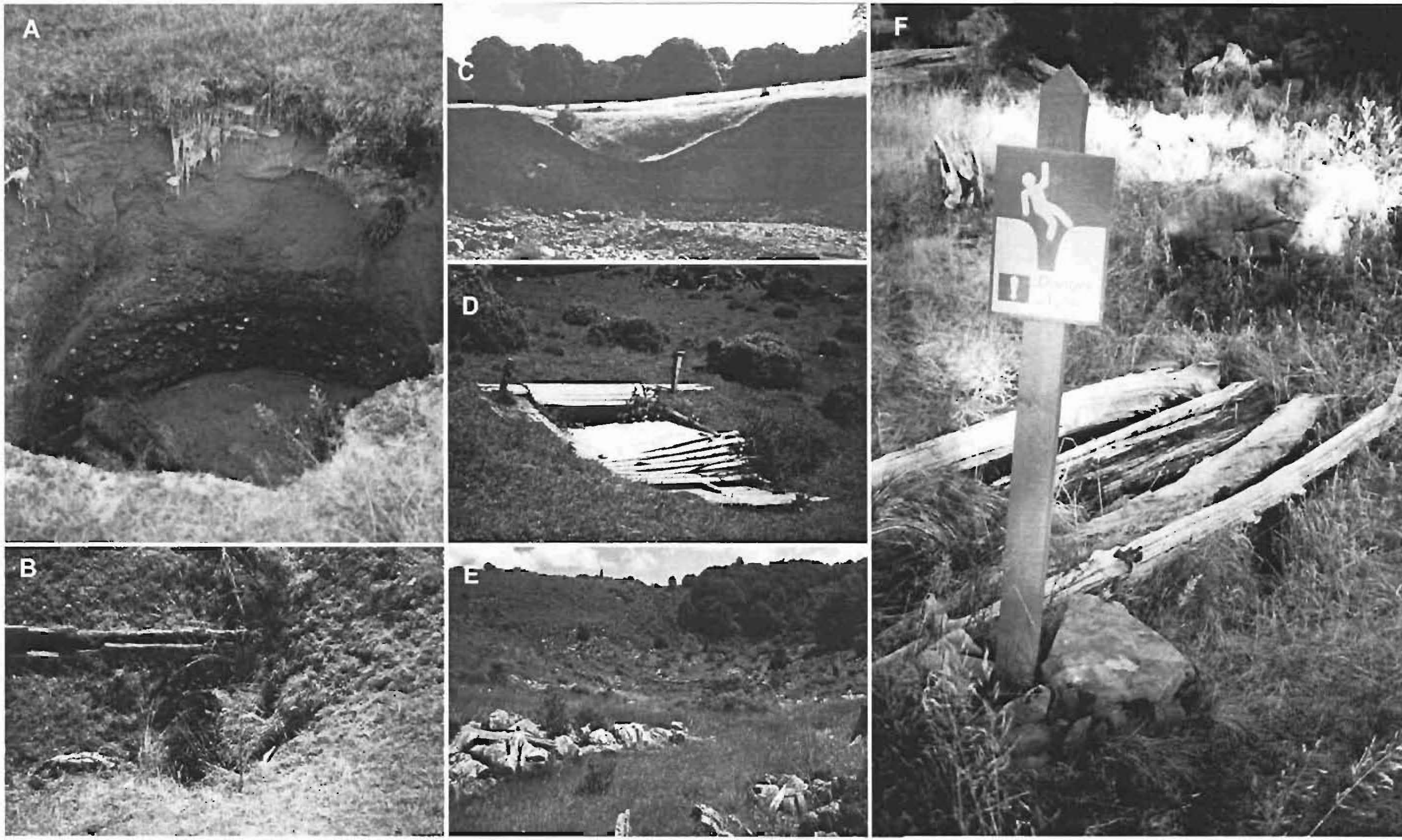


Figure 3.5. Dolines. (from top left) A. Actively forming alluvial doline ~3m across (Canaan South) B. Solution doline ~1.5m opening (Canaan North) C. Section through alluvial doline showing suffosion of sediments (Canaan South) D. Covering of collapse doline to avoid stock losses (Pikikiruna) E. Uvala, compound of solution dolines ~100 - 150m (Takaka Plateau) F. Collapse doline <1m opening (Takaka Walkway)

The main cause for formation of collapse dolines is the collapse of a cave roof near to the ground surface (Sweeting 1973, Jennings 1971). Collapse dolines, where active, are noted for the presence of toppled collapse boulders at the bottom of the vertical shaft.

The morphological features used during field classification of dolines are summarised in Table 3.1, subsidiary classes include uvalas (compound dolines) and undetermined dolines. Undetermined dolines were registered where the genesis of the sinkhole was unknown or the doline appeared to represent an indistinguishable polygenetic form. Doline numbers at each sample site were not counted.

Doline Type	Usual depth to width ratio	Usual surficial Cover	General morphology
Solution	Equal depth to width	Often exposed sides	Funnel shaped
Alluvial	low depth to width ; shallow	develop primarily in the overlying alluvium	Bowl shaped, smooth sides
Collapse	High depth to width ; deep	Exposed sides, rock collapse	Vertical shaft, small surface diameter
Uvala	Variable	Variable	Floors of the depression are made up of more than one doline

Table 3.1. Morphological features used in doline classification (after Ford and Williams 1989, Sweeting 1973, Jennings 1971).

The maximum doline diameter was visually estimated at each sample location. A bearing taken on the long axis of elongated dolines was taken by compass measurement in conjunction with surface slope, aspect and vegetation.

3.4.3 Karren Evaluation and Field Identification

The German word *karren* is used throughout karst literature as a comprehensive term to denote all small-scale solution sculpture occurring on karst bedrock (Ford and Williams 1989). While there is a multiplicity of terms for the same monogenetic end members of karren, the German terms which are most commonly used in karst literature will be applied here.

The morphological and genetic classification used for this study was compiled primarily from Bogli (1980), Sweeting (1973) and Ford and Williams (1989). It is important to note that while this classification system relies on identifying basic forms or simple end members of karren types, many transitional or polygenetic forms were visible in the field.

The genetic classification scheme of Bogli (1980) was developed on the evidence that karren type is fundamentally controlled by phases of solution that are, in turn, influenced by whether the karst bedrock was exposed (free), partly covered (half-free), or entirely covered by soil or vegetation (covered). While Ford and Williams (1989) suggest that not enough is understood about the genesis of karren to classify them in a fully genetic scheme, the morphology of the solution sculpture can be used to infer developmental processes and, in some cases, rates. Bogli (1980) asserts that rundkarren, kamenitzas and other rounded forms develop slowly as a result of solution reactions at the bedrock – cover interface. Sharpened forms like rillen-, rinnen-, tritt- and spitzkarren are formed by the first phases of solution under bare bedrock conditions. Thus the sharply sculptured free karren (such as rillenkarren) form quicker relative to the covered or half free forms (such as rundkarren) and may be regarded as comparatively younger forms (Sweeting 1973).

Karren were classified in the field according to their present-day morphological features (Table 3.2). Karren types were ascribed, where possible, to an end member karren morphological and genetic type. The sampling registered the presence of each karren class at any given sample site but did not count the total karren numbers. Illustrations of the main karren types are given in Figure 3.6.

Karren Type	Usual Width	Usual Depth	Usual length	Surface slope	Cover	Other
Kamenitza	0.05–2.0m	<0.50m	Circular	Horizontal	Part covered	Also known as solution pans
Kluftkarren	Fracture-controlled, Variable	Fracture controlled, Variable	Fracture controlled, Variable	Variable	Part covered/ Covered	Also known as grikes
Meander-karren	<2cm	<2cm	Variable	Gently inclined	Exposed	Wandering channel form
Rillenkarren	1-3cm	1-2cm	<0.50m	Inclined (steep)	Exposed	Rills, form quickly
Rinnenkarren	20-50cm	10-40cm	0.50-2.0m	Inclined (moderate)	Exposed	Runnels, often transitional
Rundkarren	10-50cm	10-40cm	0.50-5.0m	Inclined	Covered	Rounded channels
Spitzkarren	10-40cm	10-40cm	0.50-2m	Inclined	Exposed	Peaked crests
Trittkarren	10-30cm	<5cm	Circular	Gently inclined	Exposed	Resembles heelprints

Table 3.2. Summary of morphological features used to identify karren (adapted from Ford and Williams 1989, Bogli 1980, Sweeting 1973, Jennings 1971). Further descriptions of karren forms are provided in the glossary.

Additional morphological information such as the length and width of the forms, the soil or vegetative cover, and associations with major karst landforms was noted during the field sampling.

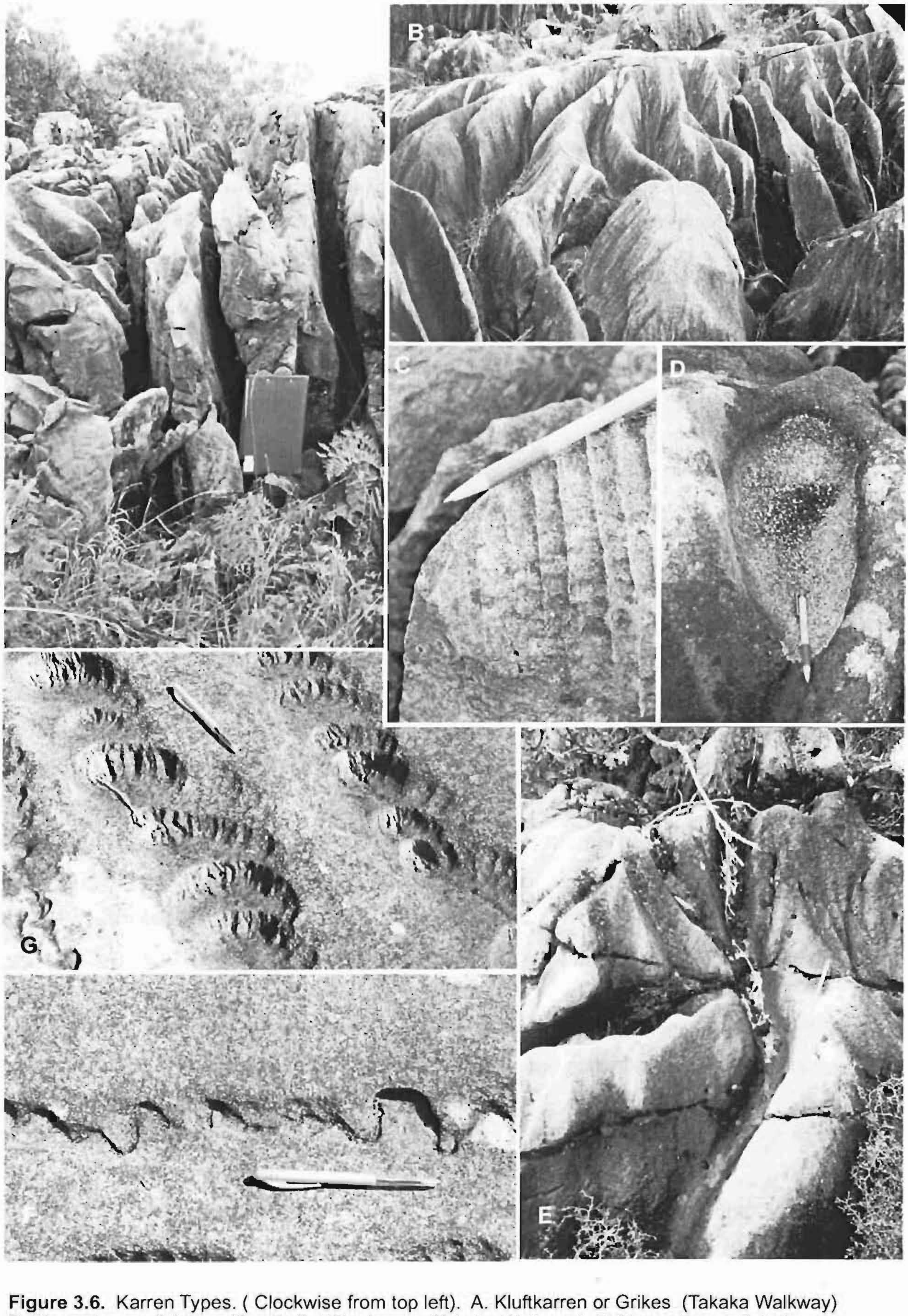


Figure 3.6. Karren Types. (Clockwise from top left). A. Kluftkarren or Grikes (Takaka Walkway) B. Rinnenkarren (Plateau Karst) C. Rillenkarren (Takaka Walkway) D. Kamenitza or Solution pan (Takaka Plateau) E. Rundkarren (Canaan) F. Meanderkarren (Marble Acre) G. Trittkarren (Marble Acre)

3.4 Non-parametric data analysis

The g test (G), a modified chi squared test (x^2), was used to test the significance of the categorical results (White 2001). The g test compares the observed landform frequency data with a corresponding set of predicted or statistically generated figures, which would occur if the data were distributed according to the null hypothesis. The results of the statistical analysis are based on the null hypothesis that karst landforms such as dolines or karren are spatially distributed independent of the karst landform zones. The g test determines whether the difference between the observed and expected figures is statistically large enough to reject the null hypothesis (H_0). Approximately 30 observations or classifications were made in each karst zone giving sufficient samples to perform g tests (G test values are often poor when the sample population is < 5).

The formula for calculating 'G' is as follows:

$$G = 2\ \Sigma(\text{observed} \times \mathit{ln}(\text{observed} / \text{expected}))$$

Where the expected value = row total × column total / grand total. The appropriate degrees of freedom (df) are in this case one less than the number of categories (karst zones) but is also calculated: number of degrees of freedom (df) = (rows - 1) × (columns - 1). The resulting G value is compared with values in chi square tables (Appendix B) to determine if G > the critical chi square value. Where G is greater than the tabulated value then justification occurs for dropping the null hypothesis, thus inferring a link between landform frequency and the karst zones.

3.5 Lithology

The collection of lithological data was utilised in investigating the influence of lithology on landform development.

Fracture frequency measurements were carried out in conjunction with the geomorphological classification. Lithological samples used for porosity and purity analyses were collected in a two-week period in August 2002.

3.5.1 Primary porosity

The term primary porosity refers to the volume of rock occupied by empty space (White 1988). Primary porosity is important in influencing erosion of karstic rocks and the form, size and distribution of small scale solution features such as karren (Ford and Williams 1989).

The samples collected for porosity analysis were of around $5cm^3$ in size and collected in the field from outcropping surfaces. Weathered surfaces were removed during sample collection to ensure that the samples were of whole, unweathered bedrock. Around 30 samples were collected from each karst zone, with a total of 221 samples.

Primary porosity of the karst samples was determined according to the standard saturation and buoyancy technique given in Brown (1981). The samples were weighed to 3 decimal places. The buoyancy method was determined by the bulk volume method, while pore volume was obtained using the water saturation method. The samples weighed around 50 - 150 grams. The samples were oven-dried (70° C) and weighed prior to saturation. The samples were oven-dried upon completion of the porosity analyses. Any samples that did not reweigh to the pre-test weight were re-analysed. As porosity values were expected to be small, this was done to endure that limited errors were collected. Errors in the primary porosity figures may have resulted from samples with very small diaclases or with variable weathering. Porosity (n) was calculated according to the following formulae:

$$\text{Saturated surface dry mass } (M_{sat}) = \text{saturated rock mass} - \text{whole rock mass}$$

$$\text{Grain weight } (M_s) = \text{saturated submerged mass } (M_{sub}) - \text{whole rock mass}$$

$$\text{Bulk volume } (V) = M_{sat} - M_{sub}/P\text{water}$$

$$\text{Pore volume } (V_v) = M_{sat} - M_s/P\text{water}$$

$$\text{Porosity } (n) = 100V_v/V$$

$$\text{Dry density of rock } (Pd) = M_s/V$$

3.5.2 *Fracture frequency*

Taken as a composite measurement of all entities where rock is absent (including joints, fractures, diaclases and faults), fracture frequency is used in this study to indicate any structural feature or discontinuity, and to infer permeability. The permeability of a rock is its ability to transmit fluid, and in carbonate rocks, is of fundamental importance because it controls the surface and subsurface drainage systems that are an integral to karst formation (Ford and Williams 1989).

Approximately six measurements were taken at each sample site by placing a 30cm ruler on the outcropping karst rock and counting any structural discontinuity that intersected the line. Measurements (number of fractures per unit length) consisted of pairs, with each line perpendicular to the other to allow for preferential structural lineations in the karst and to avoid subjectivity in sampling. A total of 686 fracture frequency measurements were taken

throughout the study area. Fracture frequency sampling was restricted to those geomorphological classification sites where outcropping carbonate bedrock was present.
No effort was made to discern between bedding, foliation, fractures, joints and so forth. In the field, it is difficult to differentiate between these features.

3.5.3 Lithological impurity

The volume of insoluble material in carbonate rocks is given as a measure of rock impurity. Karst is best developed in rocks that are purer than 70% calcium carbonate (Ford and Williams 1989).

To determine the non-calcium carbonate content of the marble and limestone, a sample, weighing between 10 and 20 grams, was hydraulically crushed to less than 5 mm. Crushing by mortar and pestle further reduced the grain size to 1-2 mm. Each sample was then weighed to 3 decimal places and placed in a clean, dry, numbered beaker. Hydrochloric acid, diluted to 10%, was added (over several days) in incremental amounts to avoid overly vigorous reactions and loss of sample. Acid was renewed until no further acid digestion of the sample was visible. Generally, 200 ml of 10% acid was required to remove all soluble carbonate, the samples immersed in acid for approximately 5 days. A total of 217 samples were analysed for compositional impurity.
After acid digest the insoluble material was washed through a Buckner funnel, using qualitative-grade, pre-weighed paper and oven-dried (50°C) overnight. Once removed from the oven, the samples were left for at least 1 hour to allow the sample to be weighed at room temperature. The residue material was then calculated as a percentage of the original sample weight:

$$\text{Impurity} = (\text{residue weight} / \text{whole rock mass}) \times 100$$

3.6 Environmental Impacts Assessment

The time available in this study and the difficulties associated in distinguishing and collecting quantitative data on human induced environmental impacts necessitated selective data collection.
Qualitative observations and information on impacts are presented in Chapter seven.

3.6.1 Soil depth sampling

Because deforestation is very widespread throughout in the study area, the environmental impacts evaluation focused on quantifying soil erosion or degradation. Soil depth sampling

(Hicks 2001) was used to assess the relative soil or sediment loss when an area is modified or deforested.

The sampling comprised a total of 180 soil depth measurements collected in March 2003. Three separate areas in the Takaka Walkway karst zone with an approximate 25 m^2 extent were selected (Map 2c). The availability of adjacent modified (cleared) and control (forested) sites, with similar topography and slope aspect guided selection of the sample areas. The extent of the sample areas was constrained in an attempt to limit errors caused by the natural variability in soil depths.

Six transects comprising 5 samples at 1 m intervals were laid out in the modified and control sites at each of the sample areas. A graduated steel probe (0.8m long, 0.01m wide) was hammered into the ground surface to either refusal (inferred as bedrock) or a maximum of 0.6m. The probe was withdrawn and the total depth recorded, soil depths over 0.6m were recorded as >0.6m. Soil type was also noted.

Small trenches (30cm^3), excavated in the modified and control sites at each area were utilised in identifying soil profiles and depth of surface organic material.

Site descriptions

Site 1 is located on a ridge, where the slope is approximately horizontal or less than 10°. The soil type varies from rendzic to non-calcareous sandy yellow brown earths. The modified area has approximately 20-30% outcrop, vegetation consisted of grasses and regenerating natives. The control area supports a beech forest with well developed internal stratification. Occasional outcrops of marble, covered in humus material and moss are noted in the forested site. Stock, presently cattle, are permanently restricted from entry into the site.

Site 2 is located on a sloping hillside, with an approximately 20° slope and north-easterly aspect. Soil types varies from rendzic to non-calcareous clay or fine yellow brown clay loam. The control site maintains a mature beech canopy but the understorey is disturbed in some areas by stock entry, particularly near the margins of the forest. Scattered outcropping marble pinnacles are noted in both sites. Vegetation in the modified area consists of grasses and regenerating pockets of natives.

Located in a stunted forest in the Takaka Walkway basin or depression floor, the topography in site 3 is rolling and slopes are predominantly less than 10°. Well-developed rendzic soils are predominant throughout both the control and cleared areas. The modified area is vegetated with grasses, scrub and fallen logs. Outcrop is scattered in both areas and is more common in the control area and soil is discontinuous or skeletal. Collapse dolines and grikes are commonly visible, particularly in the control area.

3.6.2 Erosion pins

The emplacement of erosion pins, located in the East Takaka area, was designed to quantify observable soil erosion on forestry tracks. The pins (150 mm x 6 mm galvanised flat-head nails) were driven into the soil surface at 0.5m apart. The single transect comprising 15 pins extended across a forestry track. Surface rills were visible in sections of the track. The depth to the ground surface from the top of the pins was measured in April and November 2002 and March 2003.

Analysis of the erosion pin sampling is limited by the lack of further transects, and the results are considered of limited value to the assessment of soil erosion.

CHAPTER FOUR – KARST LANDFORM ZONES

4.1 Introduction

This chapter outlines the results of the mapping. The detailed mapping was primarily undertaken to provide a geomorphological inventory of the karst features. The maps and the observational data presented in this chapter are used in later chapters to provide information on the workings and evolution of the karst within the study area.

Discussions in this chapter focus on:

- outlining the specific aims of the detailed mapping and highlighting the value of geomorphological mapping in relation to the understanding of karst systems
- describing the working procedures used in implementing the geomorphological mapping programme
- providing observational and mapped evidence of varying and/or characteristic karst landform assemblages within the study area

Quantitative geomorphological data used to validate the proposed karst landform assemblage zones is presented in chapter five.

4.2 Mapping objectives

Geomorphological mapping is utilised in the study of landforms, in particular, their nature, origin, processes of development and lithological composition. The maps focus on identifying surface form, surface material (soil and rock), surface processes and more occasionally landform age (Cooke and Doornkamp 1990, Demek et al. 1972).

Demek et al. (1972) state that detailed geomorphological maps are a considerable contribution to the planned and effective use of the geographical environment because they take into consideration the laws controlling the development of relief and thus, allow for an understanding of the whole natural environment. Geomorphological maps allow for the accurate recording of landform information in a map form that can be utilised in further derivative studies such as environmental surveys, site or resource planning, hazard mapping and engineering design (Cooke and Doornkamp 1990).

Geomorphological mapping was considered especially relevant to this study because information, and evaluation, of the physical environment and karst resources is required.

Geomorphological mapping was also chosen as a research method because it is potentially applicable to the environmental management issues relevant to the karst in northwest Nelson, particularly problem identification.

The specific objectives of the geomorphological mapping within the context of this research were to:

- identify landform type, distribution and lithological composition
- assist in understanding karst processes and developing a geomorphological evolution model
- aid in the evaluation and differentiation of natural and human induced changes.

Field inspection of the landforms and observations of the relationship between the forms, materials and landform response to processes was particularly useful in stimulating thought regarding genesis of the karst systems. Landform genesis is given on the maps by inference; mapped landforms or surface forms are presented as surrogates for the actual processes operating on those features (Cooke and Doornkamp 1990). For example, fluvial terraces are mapped to imply fluvial processes, or karren is mapped to indicate surface or subsoil corrosion of carbonate rocks. While some subjective information and interpretations about rates of change and landform genesis were assembled, quantitative age data was not collected as part of the field sampling.

4.3 Karst Landform Assemblage Zones

The detailed mapping and qualitative observations made during the mapping allowed for a delineation of zones that are, in this study, termed karst landform assemblage zones or karst zones. A karst landform assemblage zones is defined as those areas or units where correlating attributes such as karst landforms, topography, and soils or sediments are apparent. The initial results of the mapping identified at least seven karst zones. Further work allowed for the final definition of eight karst landform assemblage zones. The karst zones and a summary of the karst landform attributes are presented in Map 1 – Karst Land Systems Map. The karst zones as shown in Figure 4.1. are:

1) Kairuru
2) Plateau Karst
3) Canaan Downs South
4) Canaan North – Harwoods
5) Pikikiruna
6) Takaka Walkway
7) East Takaka
8) Pohara (Takaka Limestone)

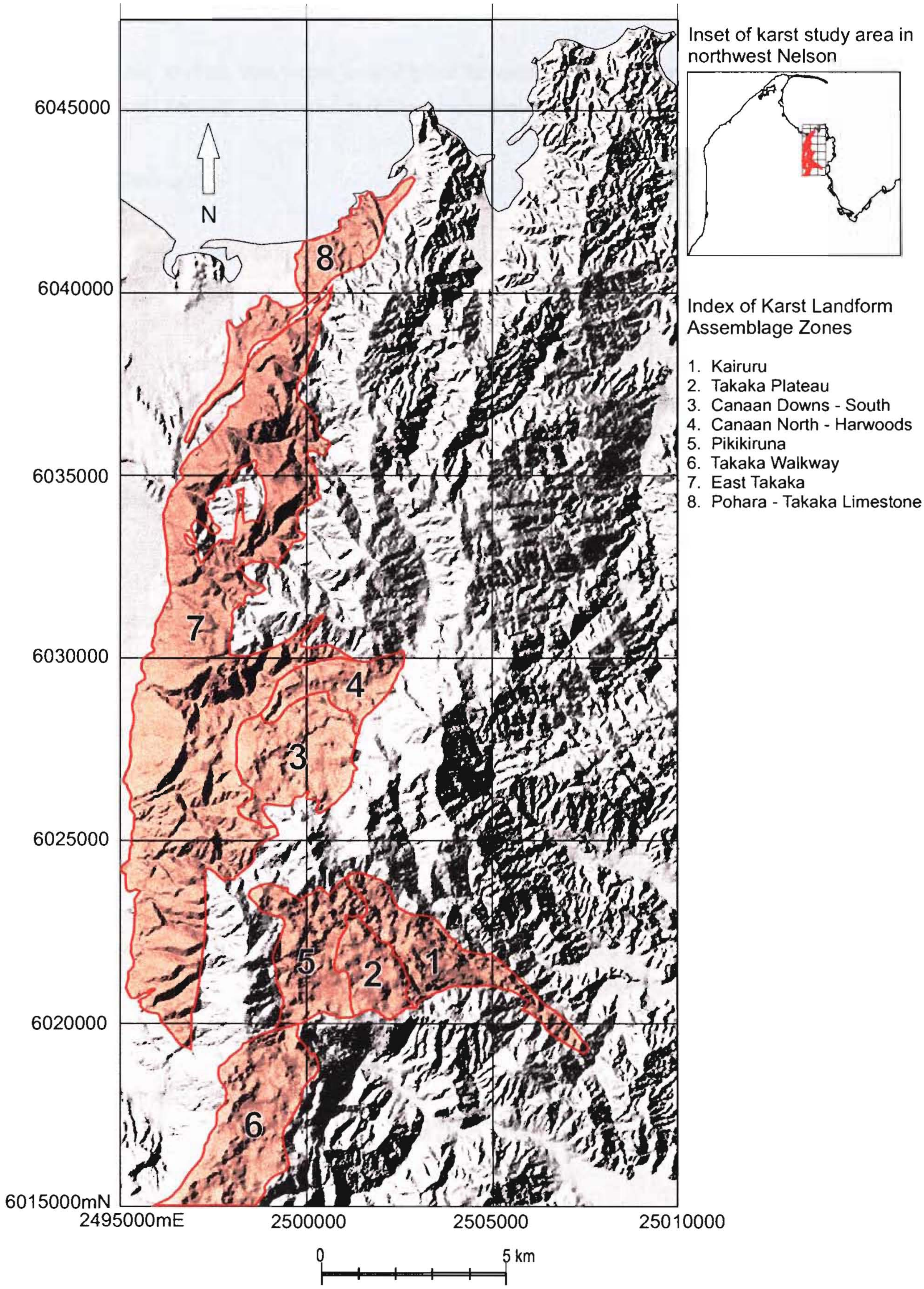
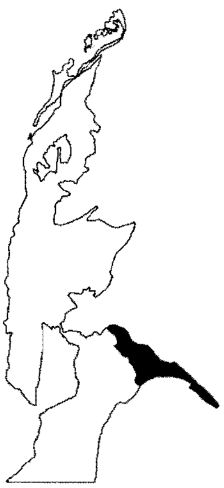


Figure 4.1. Karst landform assemblage zones. The eight karst zones shown have a similar distribution of topography, karst landforms, soils and hydrological systems. Refer to Map 1 for further detail. (DEM model based on 20m contours, New Zealand Topographic Map series 260 1:50 000. Land Information New Zealand)

It is important to note that while hydrological connections are reviewed in this section, the karst zones do not relate to the underlying groundwater divides.

4.3.1. Kairuru



Field Criteria - Kairuru karst zone is characterised by narrow, elongate plateaus dissected by south-easterly trending fluvio-karst features (Figure 4.2 and Map 2a). These features include dry valleys, blind valleys and predominantly ephemeral stream sinks. Holyoake Valley, a large v-shaped dry valley, dominates the area [Topographic map reference N26 028216].

Location and lithology - The structural mapping of Rattenbury et al. (1998) indicates that the Kairuru karst zone is faulted on three sides, the north, east and south (Figure 2.4). Non-karst rocks of the Separation Point Granites and Riwaka Complex lie adjacent to the Kairuru marble in the north and south respectively. These non-carbonate rocks comprise predominantly steep-sided, allogenic catchment areas for the Kairuru karst. The western extent of the Kairuru karst zone is bordered by a change from plateaus and valleys to the inactive polygonal karst of the Takaka Plateau karst zone. Karst continuing to the east is similar in nature to Kairuru but not long past the eastern fault the marble outcrop is restricted to one side of the valley, with Holyoake Stream running on the northern margin of the karst terrain. The marble past the eastern fault does not comprise part of the study area. Kairuru karst zone is impounded, with streams flowing across adjacent non-karst terrain to reach the sea.

The marble appears relatively coarse grained in the Kairuru zone and pale or white marble outcrops are commonly observed.

Hydrology - Waters draining the granites at the head of Holyoake Valley disappear soon after crossing the karst contact (Map 2a). Holyoake Valley is dry for more than 7 km in the central and upper sections (Williams 1992). The head of the valley, although now disjointed, extends northwards to the Granites near the Canaan Road Saddle [N26 009247]. Sinks down the Valley are active during high flow events, as evidenced by the sinks themselves, the lack of vegetation and presence of sediments and boulders indicating episodic high-energy activity. Resurging in the lower valley floor, northeast of Ngarua Quarry, a small stream flows for several hundreds of metres before sinking again. Holyoake Stream rises further down the valley and flows towards Marahau. High rainfall events cause the location of the rising to migrate further up the valley close to the base of Ngarua Quarry, as observed after rains in January 2001 and August 2002. The landowner, D. Henderson (*pers. comm.* 2002), notes that the spring is always cold, this is probably similar to the effect on the waters of the Riwaka Resurgence (Williams and Dowling 1979). Williams and Dowling (1979) note that resurgent karst waters at Riwaka, near sea level vary from 8-11°C. These waters are derived from the Marble Plateau area where temperatures are 4-5°C lower than the mean annual temperature of 12.3°C recorded at Riwaka.

The stream, according to local farmers (Henderson, D., Hobson, D. *pers. comm.* 2002), does not run dirty after heavy rain. N. McKay from Ngarua Quarry (*pers. comm.* 2002) noted that the rising 'has only ever run dirty once when there was an earthquake at least a decade ago. It ran white for about a day'. Dye tracing of sinks in the Ngarua Quarry area did not indicate a link with the Holyoake Stream risings (McKay, N. *pers. comm.* 2002).

A small outflow of water entering Holyoake Valley underneath quarry rubble appears to be drainage from allogenic stream runoff from Riwaka Complex rocks. Although indicated as a tributary of the Otuwhero River on the Takaka Topographic Map 260-N26 (Land Information New Zealand 1999) the waters, derived from non-karst surface runoff, sink along several points of the karst-granite contact and cross the topographic divide to resurge in Holyoake Stream (Williams and Dowling 1979). Surface flows outside of allogenic catchments appear to be minor and ephemeral. Autogenic inputs occur on the plateau surfaces where some ridges comprise exposed karst bedrock or where surface runoff is semi-concentrated via occasional sediment-covered solution dolines.

Karst landforms - Some dolines are irregularly spaced and aligned along dry valleys, or aligned adjacent to ridges, with a general east-southeast trend (Map 2a). Dolines commonly punctuate the lower end of blind valleys. Doline fields are restricted to surfaces where the topography is horizontal or gently sloping. The relatively small dolines (< 5m) in the fields occur as densely clustered groups. Although the actual threshold slope angle is unknown, dolines do not appear to occur on slopes steeper than around 25°. Of note, is the absence of dolines in Holyoake, and other large, dry valleys and canyons, throughout the study area (Map 2a).

Solutional features such as karren were most often observed on the plateaus and ridges. Many of the ridges and outcropping plateau areas have well-developed rinnenkarren. The more exposed ridges also have areas of rillenkarren and grike development. These ridges often have standing tree roots lying on the outcropping rock.

Caves in the Kairuru zone include Landrover, Hawkes, and Ngarua caves. The caves are predominantly semi-horizontal and may represent abandoned paleo-caves or conduits (Millar 2002). Other numerous unnamed cavities although large enough to enter at the surface appear very limited in extent and are often vertical shafts or collapse dolines.

Surficial cover - Sediment and soil in the Kairuru karst zone is generally thinner or discontinuous on ridges, and thicker in depressions and valley floors. The exception to this, is the exposed karst boulders and rubble at the base of the narrow Holyoake Valley. The rubble may be derived from relocation of boulders from upper slopes and removal of overlying surficial cover from downwashing. Many of the areas with extensive deposits of sediment are now removed from any possible source. A wide variety of soil types were noted in the field. Non-calcareous soils, more common in the Kairuru karst zone relative to calcareous soils, are predominantly found close to the karst contacts and in association with fluviokarst landforms. Rendzic soils (Kairuru soils) are more commonly located around the ridge tops.

4.3.2 Takaka Plateau

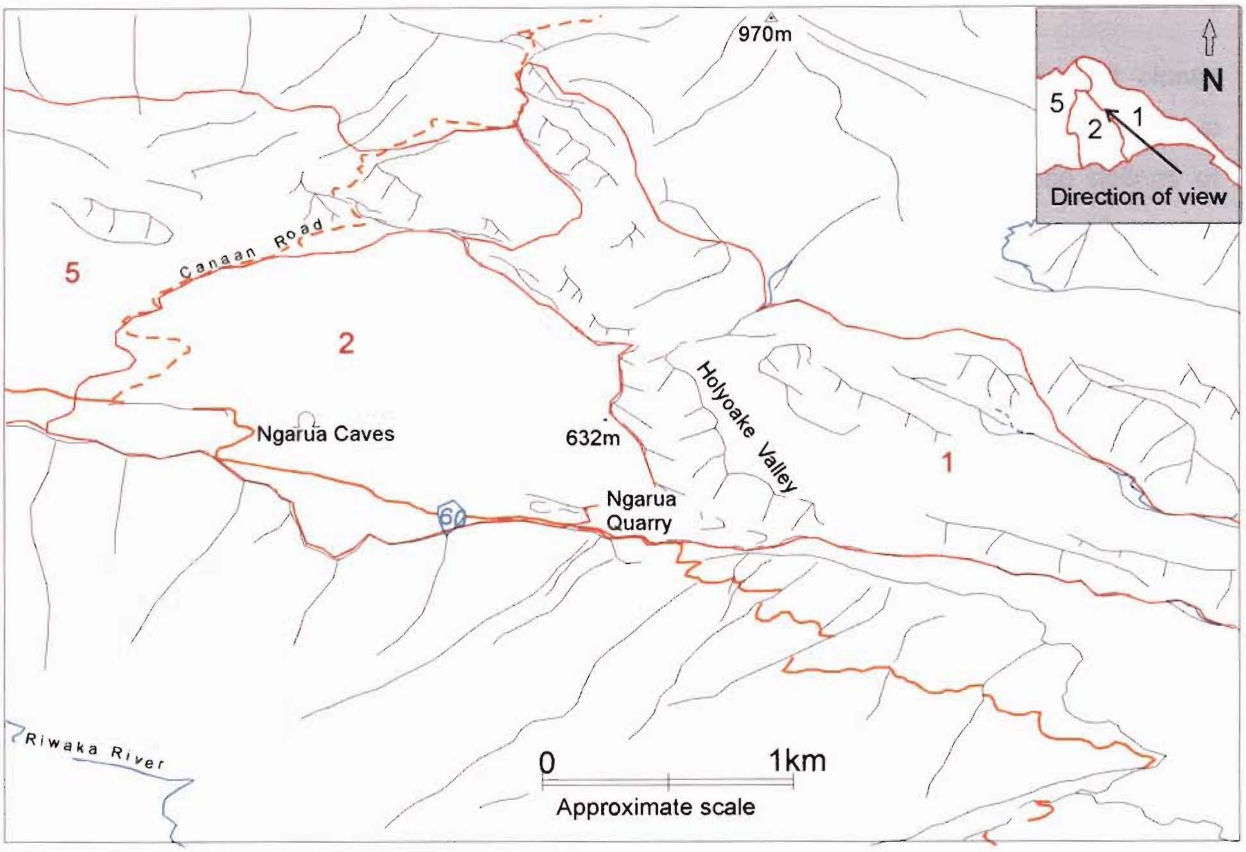
Field criteria - Considered very scenic for its large and well-shaped solution dolines, and sculptured rock outcrops, the Takaka Plateau karst zone forms an undulating land surface at around 600 m (Figure 4.2 and Map 2a). The Takaka Plateau karst is listed by Worthy (1990) as a karst feature of national importance.

Location and lithology - The plateau is bordered to the east by the Kairuru karst zone and to the west and north by the sediment-covered slopes of the Pikikiruna karst zone. The western boundary closely coincides with Canaan Road. The southern extent is defined, for the purpose of this research, by the southern most limit of the study area, State Highway 60. South of the Highway the plateau drops steeply away to less than 100 m to form the partially fault-bounded headwall of the Riwaka Valley.

Hydrology - The plateau is conspicuous on the topographic map 260-N26 (Land Information New Zealand 1999) and aerial photos for its lack of surface water. The area presently receives no allogenic point-source inputs. Where sediments cover the doline sides, the autogenic recharge is semi-concentrated into point-source drainage by the well-developed solution dolines (Ford and Williams 1989). Diffuse drainage occurs in areas with discontinuous sediment and soil cover.

Karst landforms - Many of the remnant fluviokarst features are orientated north-east, parallel to structural lineaments (possible bedding or folding) observed on aerial photographs. The dolines on the eastern side of the Takaka Plateau karst zone are often asymmetrical, and are elongated in a similar north-eastern direction (Map 2a).

Williams (1992) describes the Takaka Plateau karst as an example of inactive polygonal karst, noting that, in some parts of the karst zone, the dolines occupy nearly all of the available space. The Takaka Plateau karst zone has a high density of large dolines relative to other karst zones. The large dolines, predominantly cylindrical or funnel shaped, commonly have outcropping marble bedrock exposed in the sides.



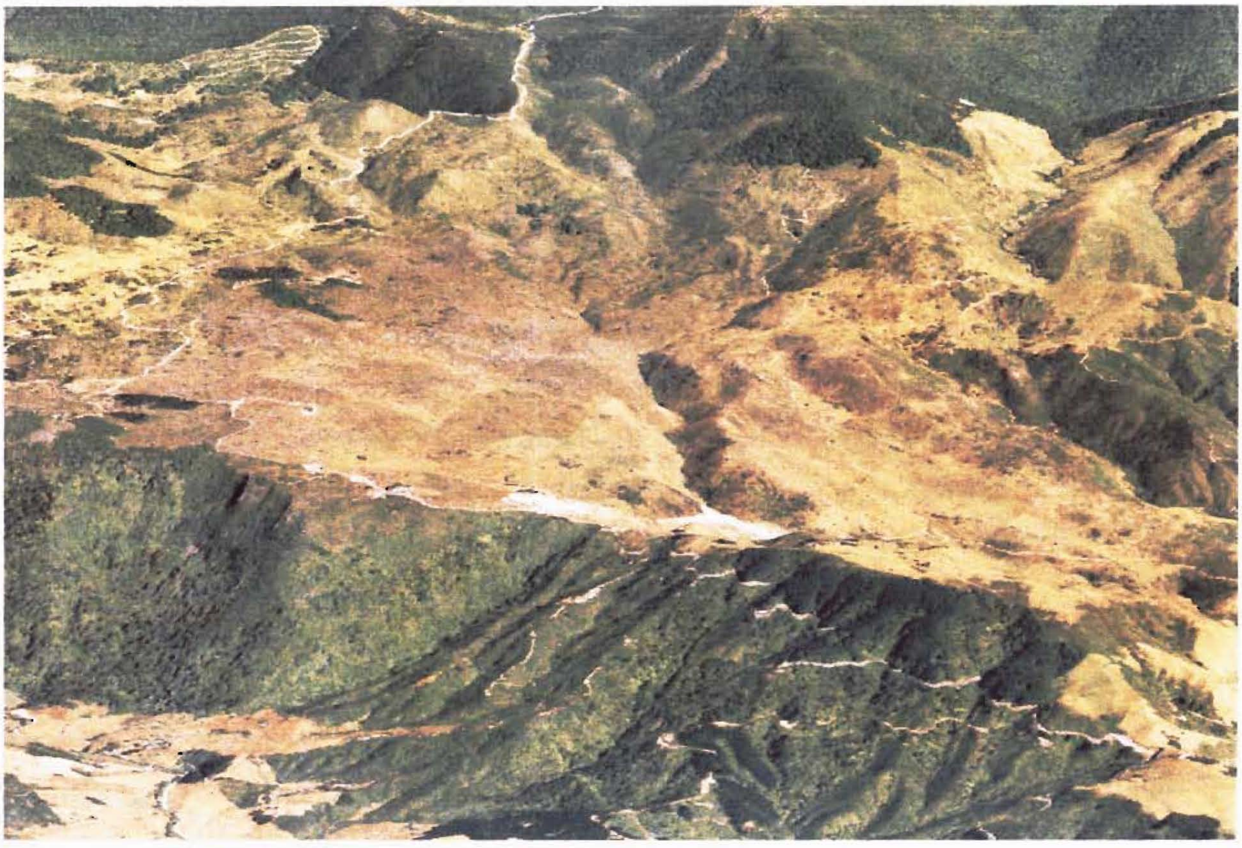


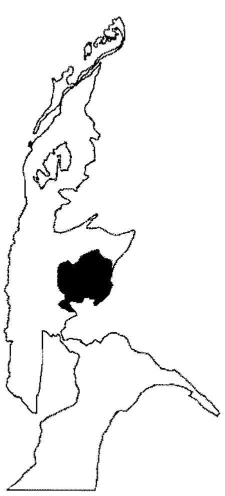
Figure 4.2. Showing Kairuru (1), Takaka Plateau (2) and Pikikiruna (5) karst zones. The plateau surface drops abruptly to the Riwaka Valley. The difference between the soil covered Pikikiruna zone and the largely exposed Takaka Plateau zone is clearly visible from the image. (DEM model based on 20m contours, land Information New Zealand, Copyright Reserved. Aerial photo from Terralink, Copyright Reserved)

Some of the largest dolines are visually estimated to be, from the uppermost closed depression contour, more than 300 m across. In some instances, dolines have coalesced to form a larger depression, known as an uvala (Map 2a). Occasional collapse dolines or tomos were observed, with an opening diameter of 1-2 m and about 3-10m deep. Some are much longer, one being the entrance to a known cave (Winter Cave).

The caves in the Takaka Plateau karst zone, Winter Cave and Black Sabbath are both entered via vertical shafts (Palmer, J. *pers. comm.* 2002). Outcropping karren, mostly rundkarren and rinnenkarren, are often found on topographic highs. The rinnenkarren in some areas is very well formed and forms the classic sculptured rock seemingly prized by local landscape gardeners. Karren is also located along structural lineations, this being especially obvious near Ngarua Caves. Scattered outcrops of rillenkarren and grikes are observed in areas with very skeletal soils. Solution basins are also occasionally observed on horizontal surfaces of larger bedrock outcrops.

Surficial cover - Soil cover in the karst zone is discontinuous, with the thicker profiles found on downslope areas and concentrated in dolines floors. Rendzic, non-calcareous and intergrade soils are noted. Many ridges are completely devoid of surficial cover. The soil in these areas where present is found pocketed in grikes and other crevasses.

4.3.3 Canaan Downs - South



Field criteria - Located in a shallow basin, the area is characterised by rolling sediment-covered downlands, with fluvial landforms, and alluvial dolines (Figure 4.3 and Map 2b).

The Canaan South karst zone meets the requirements for a polje. Worthy (1990) has registered the landform as a feature of regional importance. The nearby granites and the dominance of allogenic drainage indicate that Canaan Downs South is a border polje (Ford and Williams 1989).

Location and lithology - Originally mapped as one zone, the Canaan South and Canaan North karst zones were separated after repeated field inspection. The zone is bound to the east and south by granites, to the north by Canaan North zone, and to the west by a range of marble peaks (~ 800 m) aligned along the Pisagh Fault (Figure 2.4) and the dissected gorges of the East Takaka zone.

Hydrology - The hydrology in the zone is dominated by allogenic drainage and sinking streams. Gold (or Long) Creek which drains the granites in the northeast of the Canaan South zone forms an influent stream (Ford and Williams 1989), gradually losing flow and disappearing adjacent to a karstic scarp (Figure 3.3.f). Downstream of the flow disappearance the channel continues past the ford, but is increasingly dissected by dolines.

The site of flow disappearance migrates downstream under heavy rainfall conditions, as observed during field visits. Jordan Creek, supplying lateral surface flow derived from granites to the south and east of the area, forms an alluviated and terraced floodplain and valley. A main sink area [N26 008273], receives permanent streamflow from the granites to the east (Figure 4.3). Stream flow from the south is intermittent, during dry periods no water enters the system. In moderate flows, water flowing from the south sinks into a small cavity located close to where Canaan Road enters Canaan Downs [N26 005270]. During high rainfall events, overflow continues along the entire length of the stream channel and disappears in the main sink area (Figure 3.3.d). The main sink area, marked by a moderately developed headwall scarp, appears to be very active with four different sinks observed during the period December 2001 to Nov 2002. The size and shape of each sink opening also varied between field visits. Incision or degradation of the stream channel surface occurred during the above period. Flooding during heavy rains in June 2002 caused Jordan Creek South to flow for the entire length with an average depth of ~ 0.3 m. The waters were slightly discoloured but the channel bottom was plainly visible. Waters at the main sink area banked up to a depth of > 3m. The landowner (Greenhough, T, *pers. comm.* 2002) observed that the entire sink area becomes submerged (up to 8 m deep) during extreme floods.

Located in the southwest of Canaan South, a small, unnamed allogenic stream, with a doline-dissected channel, forms a tributary to Jordan Creek South and crosses Canaan Road in moderate to high rainfall conditions.

Several doline dissected, blind valleys, with intermittent flows are found in the west of the zone.

Karst landforms - Most of the dolines found in the Canaan South zone are formed in the thick alluvial sediments that cover the karst bedrock. These alluvial (or suffusion) dolines develop because the overlying sediment is removed vertically down karst conduits by solution and downwashing (Ford and Williams 1989). The dolines are usually less than 5 m in diameter and elongated in the downslope or down-drainage direction (Map 2b). The alluvial dolines occur as scattered groups or doline fields aligned along fluvial or fluviokarst features. Several large shallow dolines located on the highest terraces have become permanently water filled, doline ponds. On the lower, intermittently flooded terrace surfaces the dolines form steep, gravel sided, unvegetated holes. Several dolines, close to the main sink area, changed noticeably in form or size during the study period.

With marble outcrop restricted to scarps and headwalls, the distribution of karren is also limited. The karren, where present, comprises rundkarren, rinnenkarren or grikes, with no rillenkarren observed. Intermediate forms between rundkarren and rinnenkarren were common.

Although several cavities large enough for a person to enter were observed, none appear to extend more than several metres.

Surficial cover - Sediment cover in the zone comprises rounded to sub-rounded, unconsolidated, clast supported alluvium. The boulders are predominantly granitic in origin. Depths up to 8 m were noted in terrace scarps. The total depth of the cover in the main valley is unknown. Rendzic soils in the karst zone are very limited.

Subsidiary zone – Of secondary importance to the Canaan South zone, is the Marble Acre karst pavement (Map 2b). Although very limited in extent (~1 km), the Marble Acre karst is very different geomorphically to the main karst zones. The karst occurs as a sub-horizontal or gentle, northeasterly-sloping marble pavement close to the western border of the Canaan South Zone. The area is characterised by solution features such as trittkarren and meanderkarren. These features, in contrast to rund-, rinnen- and rillenkarren, only occur on gently sloping surfaces. The area also supports well developed grikes and clints. A small stream traverses the area, channelled by a very small, incised, sediment filled valley. The location of the stream source or sink is unknown.

4.3.4 Canaan North-Harwoods

Field criteria - The zone is dominated by a large linear, u-shaped dry valley, extending south-westwards from the Wainui Saddle to Harwoods Hole (Figure 4.3 and Map 2b). In the upper reaches, the valley is asymmetrical, with a steeper, marble bedrock exposed western wall and a gentle, quartzite - alluvium covered eastern side. In the lower sections, along the Harwoods Hole track, the valley narrows and exposed marble is present on both sides. North of Wainui Saddle, the Wainui River flows in a linear, non-karst valley to emerge at the coast at Wainui Bay. Williams (1992b) uses the Canaan North – Harwoods Valley as an excellent illustration of 'headward retreat of streamsink sites in a karst system'.

Location and lithology - Canaan North karst zone lies in a valley surrounded on the eastern and northern borders by the granite and gabbro peaks of the Pikikiruna Range. Canaan North is separated from Canaan South by a marble ridge. The zone, extending to the west towards Harwoods Hole, is terminated abruptly by the deeply incised Gorge Creek.

Hydrology - Waters draining off the adjacent non-karst rocks enter the karst soon after reaching the contact. The present-day principal point of entry is Homestead Sink, an allogenic sink draining runoff from the Wainui Saddle and western slopes of the nearby granite peaks (Map 2b). Homestead Sink [N26 033 297], marked by a crevasse in a well-developed headwall, occurs at the downslope end of a blind valley. In moderate to heavy rains the Canaan North Valley maintains surface flows which sink at various locations along the valley floor. Originally, waters flowing down the valley disappeared underground at Harwoods Hole and re-emerged at Starlight Cave, in Gorge Creek. The drainage has progressively retreated northwards from Harwoods Hole/Gorge Creek towards its present location at Homestead Sink, leaving Harwoods Hole and the lower valley as a dry shaft and dry valley respectively (Williams 1992b). The water from Homestead Sink now resurges 145m lower down Gorge Creek Canyon in Gorge Creek Cave (in the East Takaka karst zone). Flows from the Gorge Creek Cave rising disappear underground within a couple of hundred metres to resurge at Spittals Spring in the Takaka Valley (Williams 1992b).

Observations by J. Richards (*pers. comm.* 2002) during a visit to Starlight Cave after rainstorms indicated that water levels were higher than observed during previous visits. The higher levels were interpreted as a response to heavy rainfalls of the previous days. Still damp, remobilised sand deposits left by the receding waters indicated that the water levels were around 0.5 m higher prior to visiting the Cave. The water was running very clear. The well sorted (1-2 mm) quartz sand, is most likely derived from granites. Larger grain size (1-2 cm) deposits captured in the streambed comprised well rounded pebbles of granite, sandstone, quartz and marble. The marble pebbles were elliptical and very well rounded.

Karst landforms - Dolines in the Canaan North zone are commonly found in clusters on or near the contact or aligned along the valley floor (Map 2b). Solutional and alluvial dolines were noted in nearly equal abundance. Fields of alluvial dolines are observed in areas where thicker regolith profiles overly the marble bedrock.

Karren are predominantly rundkarren and rinnenkarren. Occasional rillenkarren are observed, especially in the western valley sides where karren fields are more prevalent.

Caves in the area include Ed's Cellar (259 m deep), Harwoods Hole (176 m deep on low side), and Dog-leg Cave. The caves predominantly consist of deep, vertically extensive shafts (Palmer, J., Millar, I. *pers. comm.* 2002, Worthy 1990)

Surficial cover - The surficial cover is mostly non-calcareous and occurs as a continuous cover in the valley floors and downslope areas. Soil cover is very minimal on ridges and the lower valley. Cut standing tree trunks are exposed on the bedrock ridges. Several colluvial fans are found entering the valley from the granite slopes.

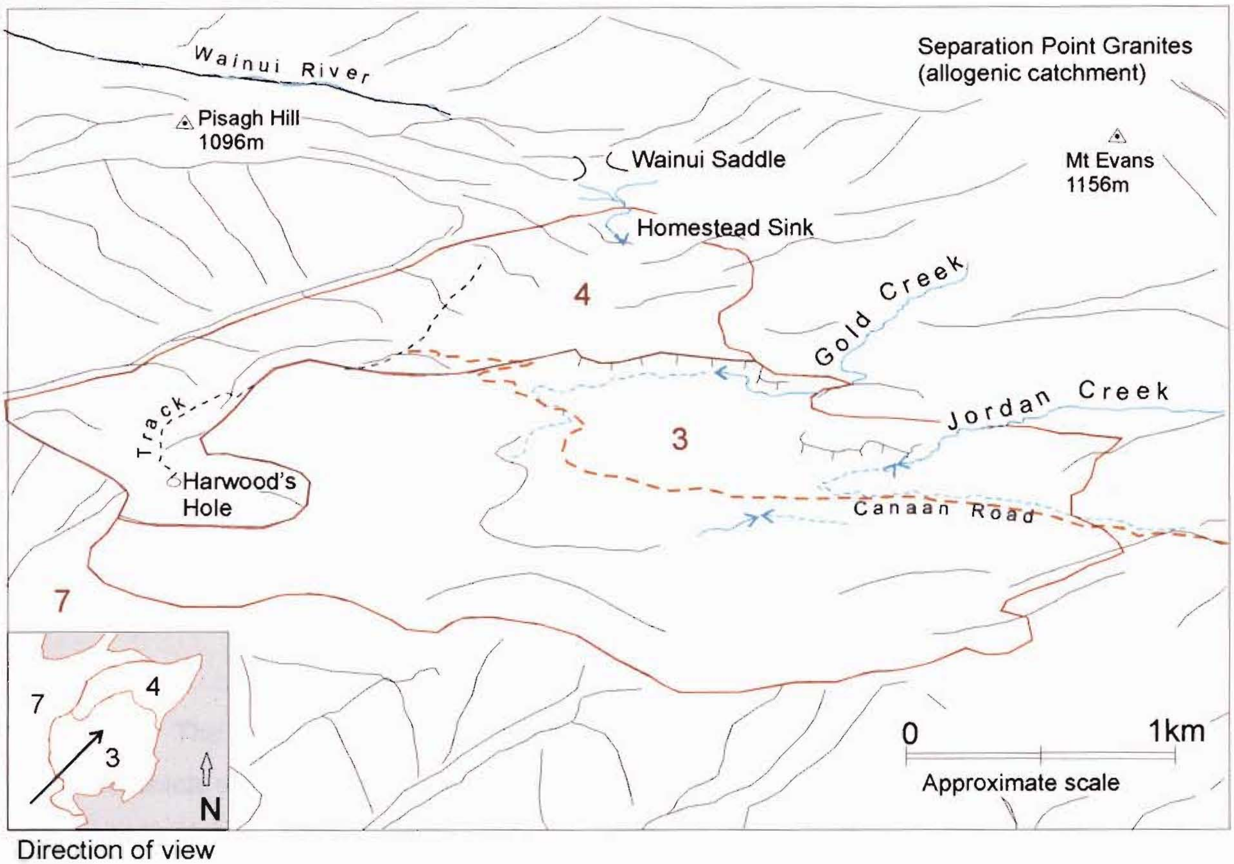


Figure 4.3. Showing Canaan South (3) and Canaan North (4). The rolling downlands are truncated in the foreground by the dissected topography of Gorge Creek and the Pikikiruna fault escarpment, East Takaka (7). (DEM model based on 20m contours, Land Information New Zealand, Copyright Reserved. Aerial photo from terralink, Copyright Reserved)

4.3.5 Pikikiruna Karst

Field criteria - Predominantly continuous surficial cover, allogenic drainage, allochthonous sediments, and alluvial dolines typify the Pikikiruna karst zone. Although less visually impressive than the adjacent karst zones because of a lack of surface bedrock exposure, much of the zone occurs as sediment covered rolling hills and blind valleys, the zone hosts numerous, extensive cave systems. (Figure 4.2 and Map 2a).

Location and lithology - Situated to the west of the Takaka Plateau karst zone and to the north of the Takaka Walkway zone, the Pikikiruna karst zone lies to the east of the Pikikiruna Schist. Non karst rocks (Separation Point Granites) also lie to the north of the zone.

Hydrology - The southern part of the zone features a flat-floored, sediment-covered blind valley in which waters running off the schist submerge into several sinks (Sawmill Sinks) located at the base of a well developed, approximately 40 m high headwall (Figure 4.4). The headwall, forming the roadside escarpment [N26 998205], is one of the higher headwalls in the study area. The southernmost creek appears to be permanent, while many of the other stream channels are only occupied during moderate to high rainfall conditions. In the north of the zone, allogenic drainage enters the karst via sinks associated with caves such as Perseverance, and the Swiss Maid - Green Link – Middle Earth system. The caves are all located at the down slope termination of sediment filled blind valleys. During mean or low flows the water does not enter the end-point cave sink but disappears soon after crossing the marble contact. Waters entering the Greenlink and Middle Earth caves re-emerges at the Riwaka Resurgence (Williams 1992b, Williams and Dowling 1979). Anecdotal evidence from numerous local landowners indicates that during sawmilling in the 1950s, sawdust emerged at the Riwaka Resurgence. More recently, cave divers have found sawdust in an airfilled chamber beyond the first two submerged sections of the Riwaka Resurgence Cave (Millar 2002).

Waters entering the Swiss Maid – Greenlink – Middle Earth Caves during a rainstorm (June 2002) flowed to the cave sinks for one day only and were (surprisingly) relatively clear of suspended sediments. Obvious during the visit was some flooding and surface inundation of grassed areas immediate to the cave entrances.

Internally, allogenic recharge to the zone occurs where significant depths of sediment cover occur. Where sediment cover is thinner, drainage is dominated by autogenic recharge.

Many of the fluviokarst features trend north-south. Elongated blind valleys found in the southern part of the zone appear to drain in a southerly direction towards the apparently inactive Hiki's Sink [N26 009206].

Karst landforms - Alluvial dolines appear to be more prevalent than solutional or collapse dolines in the Pikikiruna zone. Several isolated collapse dolines situated on sloping valley sides were observed in the east of the zone. Alluvial dolines are principally found in association with sediment-covered, blind valleys, in which the dolines are aligned in the drainage direction (Map 2a). A relatively large number of undetermined dolines were noted in this zone. These dolines predominantly occur in sediment but have an outcropping 'tor' of marble in the doline wall.

The Sawmill Sink area is similar to the Canaan polje in that the sink area has steep sides, centripetal drainage and an alluviated valley floor.

Perseverance Cave is one of the few caves on the Takaka Hill to develop gently sloping passages. The cave, discovered in the 1980s is at least 3km long and 315m deep. The gently dipping passage slopes may relate to the underlying granite basement (Millar 2002).

The shafts of the Greenlink (940m long, 394m deep) - Swiss Maid - Middle Earth (1.3km long, 284m deep) cave system are predominantly vertical (Worthy 1990). Greenlink Cave with the connection to the Riwaka Resurgence has a hydrological depth of ~ 700m and is, according to Worthy (1990), one of the deepest caves systems in New Zealand.

Outcropping marble in the area is scattered. Rundkarren and rinnenkarren are observed, with some of the less well-formed rinnenkarren developing on rounded marble subcrops. No rillenkarren was observed during the field mapping.

Surficial cover - Soils are predominantly non-calcareous, yellow-brown earths. While depths greater than 5m are found in road cuts, the maximum depth is unknown. Sediment cover increases to the west, with soil/sediment cover becoming more variable towards the Takaka Plateau zone. The marble-schist contact is not exposed at the surface. The depth of cover in the lee of the Pikikiruna schist may be sufficiently thick as to limit karst development.

4.3.6 Takaka Walkway

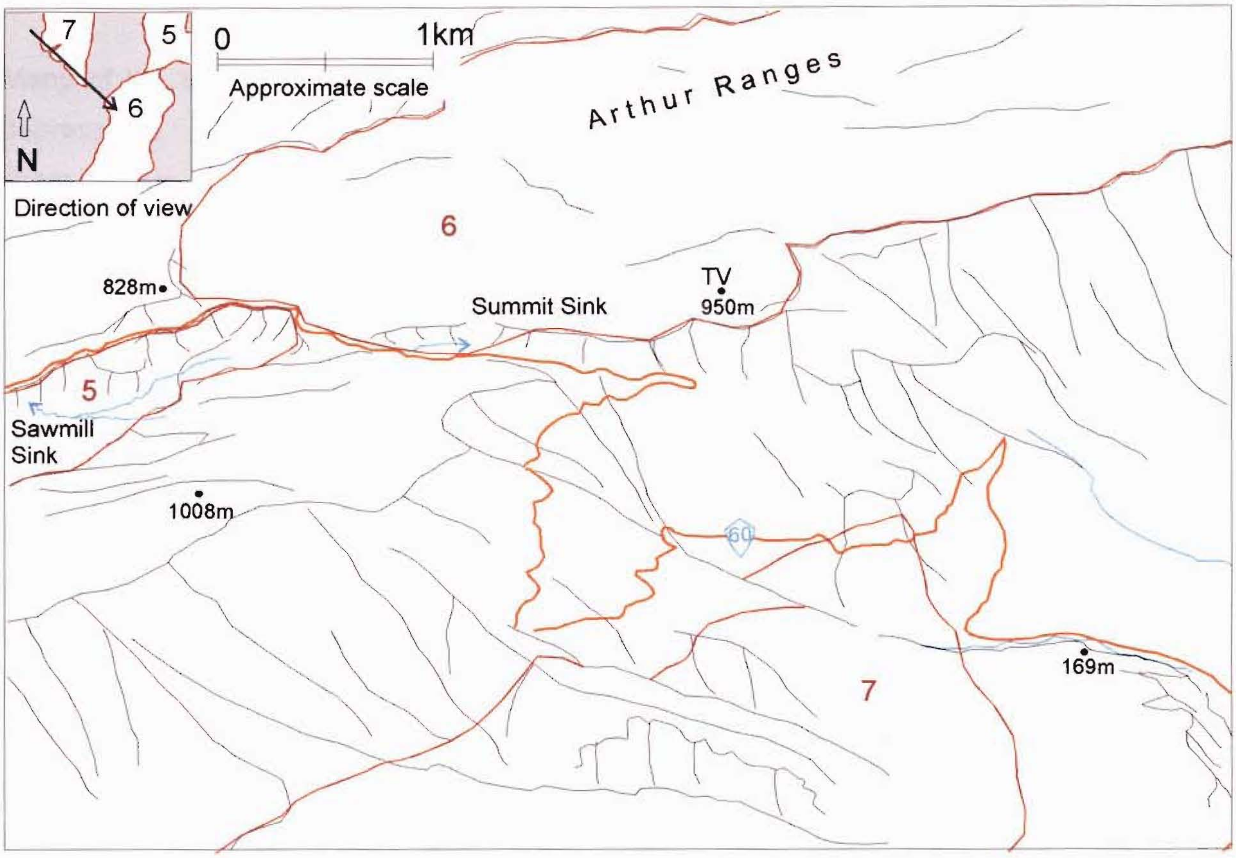
Field criteria - The Takaka Walkway zone is distinguished by the fractured and brecciated appearance of the marble, the high density of outcropping surfaces, and collapse dolines (or tomos). Figure 4.4 and Map 2c highlight the karst features.

Location and lithology - The Takaka Walkway karst zone is located south of State Highway 60 on the western edge of the Takaka Hill. For this research the detailed study of the karst zone is restricted to the Takaka Walkway and immediately surrounding environs. The zone forms the northern limit of the Arthur Range. Continuing southwards, the Takaka Range comprises a gentle, easterly sloping marble plateau, falling away to the west and east to the Takaka and Riwaka Valleys respectively. A prominent ridgeline consisting of Pikikiruna schist lies to the north of the Takaka Walkway karst zone. The schist forms the southern extent of the Pikikiruna Range. A fault forms the contact between the marble of the Takaka Walkway and the schist. The marble escarpment running east-west parallel to State Highway 60 is the surface expression of this movement (Map 2c). The Pikikiruna Fault, lying directly to the west of the Takaka Walkway zone (refer to Figure 2.4), has uplifted the plateau surface by up to 950m.

The Takaka Walkway is covenanted by the Queen Elizabeth II Trust and, although still a working farm, is accessible via walkways to the public (Harwood, D. *pers.comm.* 2002). A vantage taken on a fine day, near the television receivers at the summit of the Range (Figure 4.4), affords spectacular 360° views of Mt Arthur, Farewell Spit and the Marlborough Sounds.

Hydrology - A short, unnamed stream (not marked on the topographic map) drains from the schist into Summit Sink (close to the Takaka Walkway carpark). The sink [N26 987194] is located close to the marble contact and lies at the foot of a ~50m high, fault-controlled headwall (Map 2c). Waters entering the Summit Cave system has been traced by Williams and Dowling (1979) to the Riwaka Resurgence (refer to Chapter 2.7). Found on the western side of the plateau, the Aaron Creek Resurgence (waters traced from Olympia Cave) forms a tributary to the Takaka River. The Olympia cave entrance occurs at the end of a blind valley, with the valley floor covered by non-calcareous sediments (Richards, J. *pers. comm.* 2002). Other minor allogenic inputs may be derived from the interbedded clastic deposits found in the area. The high frequency of fractures in the bedrock and the lack of alluvial and solution doline development indicates that autogenic recharge to the area is predominantly diffuse.

Karst landforms - Collapse dolines, common to the area are usually less than 1m in diameter at the surface opening and appear to be shallow (<2m), with boulders and rubble visible at the base of the shaft.



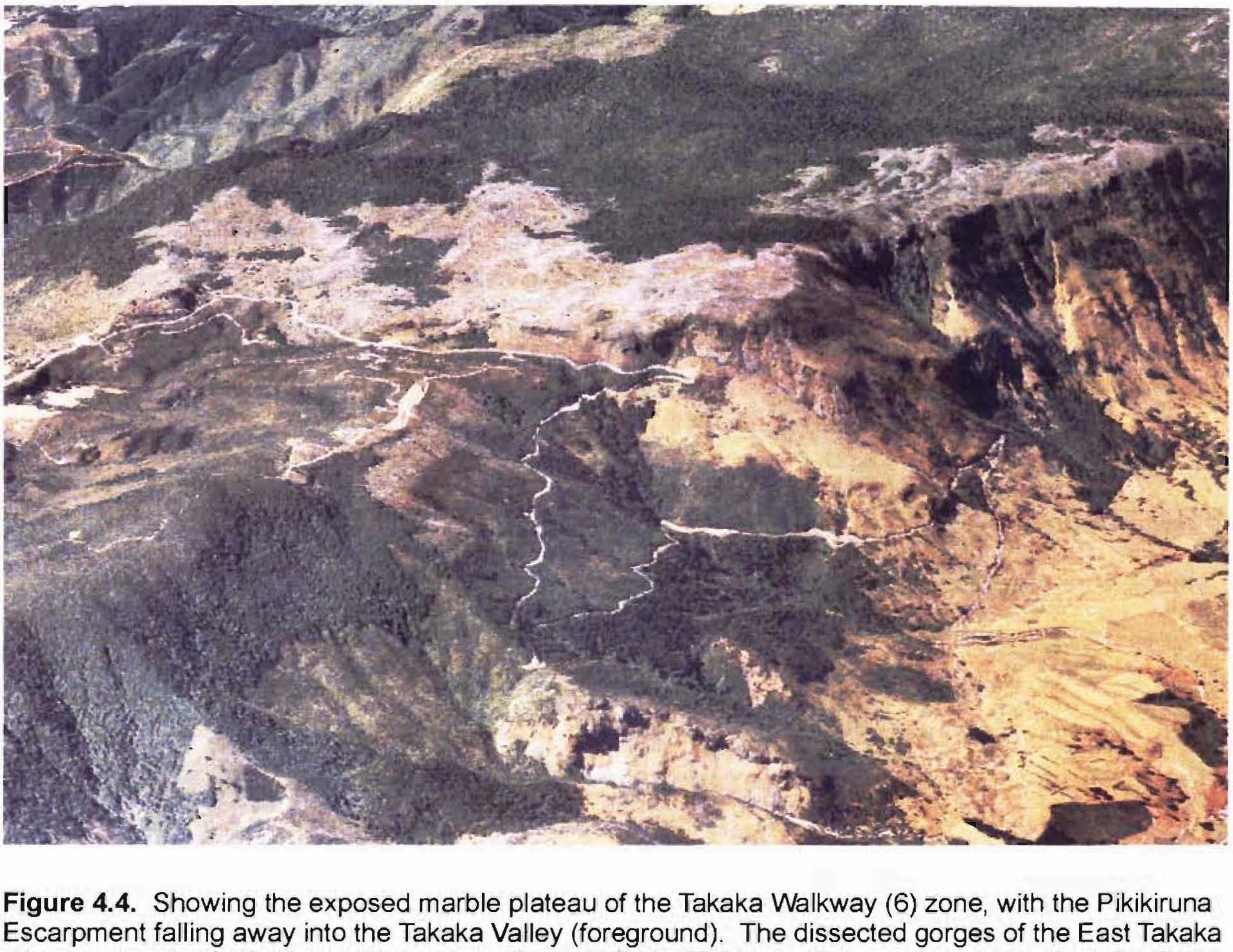


Figure 4.4. Showing the exposed marble plateau of the Takaka Walkway (6) zone, with the Pikikiruna Escarpment falling away into the Takaka Valley (foreground). The dissected gorges of the East Takaka (7) zone are also in the fore of the image. Sawmill Sink (Pikikiruna (5) karst zone) is to the left. (DEM model based on 20m contours, Land Information New Zealand. Crown Copyright Reserved. Aerial photos from Terralink. Copyright Reserved)

Many of the tomos are sited at the downslope end of small, very shallow sediment-filled depressions. The depressions sometimes form an asymmetric blind valley end to small linear valleys eroded in the interbedded mudstone – sandstone sequences. The shallow depressions and tomos, are occasionally observed on or close to the interbedded mudstone – marble contact.

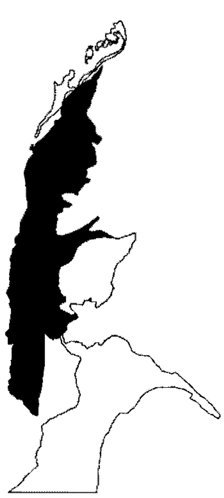
Large depressions, as seen from aerial photos, may be degraded or poorly formed solution dolines or uvalas and the general karst topography appears similar to the polygonal karst of the Takaka Plateau. In the field, however, the basins often occur on the side of slopes and do not form well-developed enclosed depressions.

Karren, predominantly rinnenkarren and grikes, are widespread in localised areas particularly where entire hillsides are bare of surficial cover. These karren fields (or karrenfelds) are especially common on topographic highs. Rillenkarren is relatively common compared to other zones and forms 1-2cm wide, 10 - 30cm long flutes. Rillenkarren is particularly well formed where the rock surface is less fractured. Some crests between the karren covered sides are very sharp and may comprise spitzkarren. Moss and lichen, growing in fractures and diaclases are very common in the exposed karren fields.

Known caves in the area include Summit Cave, the associated Summit Tomo and Olympia Cave.

Surficial cover - Ridges in the Takaka Walkway zone are predominantly bare from surficial cover with thicker soil and sediment profiles found on slope sides and in topographic lows. Soil cover and type varies widely, as evidenced in track cuttings along the walkway. The rendzic soils, well developed on more exposed areas, are black-grey and directly overlie marble bedrock. Non-calcareous soils occur in discrete areas and range from brown soils with angular fragments of iron-rich, highly weathered rock to yellow-tan soils with rounded boulders of diorite (or possibly gabbro).

4.3.7 East Takaka Karst



Field criteria - The zone is characterised by east-west trending, deeply incised, v-shaped, karst gorges with interconnected ridges, marble scree slopes and sinking allogenic streams. Several, small, isolated plateau surfaces occur in the Rameka - Dry Creek areas (Figure 4.5 and Map 2d).

Location and lithology - Extending around 18 km from State Highway 60 to the northern limit of the marble, the East Takaka karst zone covers almost the entire length of the study area. Associated with the Pikikiruna Fault Scarp, the zone extends from the Takaka Valley (~100m a.s.l) to the west, to the Pikikiruna Range (up to 900m a.s.l) to the south- and northeast.

The central part of the East Takaka Zone is intruded by rocks of the Rameka Igneous Complex, and is bordered to the east by the Canaan karst zones. The bedrock is fine grained and, in some areas of the zone is moderately to highly fractured. Structures are easily observed in aerial photographs and in the field, and appear to trend north-south.

Hydrology - Although the Pikikiruna Fault scarp continues southwards of State Highway 60, recharge in the karst south of the East Takaka Zone is autogenic and the escarpment surface less incised by gorges.

Gorge, or stream, incision of the plateau varies in the East Takaka zone. In the southern part of the zone, where the marble is adjacent to the Pikikiruna schist, the streams are spaced closer together relative to the central section. In the central section, where the karst is bordered to the east by the Canaan plateau, the gorges are very well developed, and scree slopes are common. The Rameka Complex intrusions (Map 2d), evident as slope changes across contacts, and valleys aligned along contacts complicates the topography of the central zone. The spacing between incised streams decreases again northwards of the central section. Sediment cover is thicker and more continuous in the southern and northern sections of the zone. The southern and northern sections of the zone are immediately adjacent to non-karst rocks (Map 1).

The Ironstone, Scott, Gorge, Rameka and Kite Te Tahu Creeks and Dry River are all examples of karst gorges (Map 2d and Figure 4.5). Many of the gorges are steep sided (> 35°) and heavily vegetated. Presently Ironstone Creek is the only waterway to maintain surface flows over the length of its channel. Other waterways are ephemeral, the location of the sink and resurgence dependent on rainfall conditions. Waters entering the East Takaka zone recharge the aquifers of the Takaka Valley and/or contribute flow to the Takaka and Motupipi Rivers.

Relative to non-karst streams, surface water in the karst when flowing, is often clear and free of sediment. Rameka Creek, for example, only runs dirty after approximately 50 – 100mm of rain and then only if it has been dry for a period prior to that (Sims, J. *pers. comm.* 2002).

High energy events in the gorges are not uncommon. Residents (Manson, B. and J. *pers. comm.* 2002.) close to the Gorge Creek outlet, note that during floods, boulders in the gorge can be heard 'rumbling'.

Outside of the gorges, the drainage is dominated by autogenic recharge, particularly on the outcropping marble ridges and scree slopes, and in the small plateau areas.

Karst landforms - Collapse dolines are commonly observed along the front of the Pikikiruna escarpment and on the plateaus. The shafts are usually < 2m in diameter and extend less than 5m in depth. Doline development appears limited on steeper slopes, dolines are almost entirely absent from the sides of the gorges and the escarpment, with the exception of a small area close to the East Takaka Road. Symmetrical, sediment-mantled solution dolines are found where the surface slope is moderately gentle. As with Kairuru, the dry valleys lack doline development. Alluvial dolines are found on sediment covered plateau areas (Map 2d). Solution dolines are more commonly associated with blind valleys

Karren type and distribution is variable. Rundkarren and rinnenkarren are both common, with rillenkarren present on exposed ridges. Where fracturing of the bedrock occurs, karren development is limited.

Rawhiti Cave, located in the side of the Dry River gorge, is distinctive because of the large entrance (around 50 metres wide and up to 20m high), and the prevalence of tufa stalagtites growing towards the light near the cave entrance (Baird, J. *pers. comm.* 2003).

Surficial cover - Soil type is variable, and rapid changes between calcareous and non-calcareous soils are visible over small distances. Well-developed rendzic soils are commonly observed on the sloping escarpment, as are numerous depressions characteristic of tree fall hollows, with a downslope soil mound. Soil cover in the gorges is discontinuous, soil depth or outcrop density apparently related to soil type. Rendzic soils are more likely to be located in or around outcropping marble areas, while non-calcareous soils are marked by smooth, soil covered slopes and surfaces. Variations in soil type and distribution are particularly evident in the Rameka area.

Unconsolidated sub-rounded, matrix-supported, non-karst gravels are found on one of the small plateau surfaces - 'The Basin'. The Basin [N26 994347] is located south of Manson Cave and contains numerous cut standing tree trucks. These deposits, as evidenced in alluvial doline walls, are greater than 3m thick and are being actively downwashed into the underlying marble bedrock. The deposits are presently removed from any source.

4.3.8 Pohara-Takaka Limestone

Field criteria - The Pohara karst zone features outcropping ridges and scarps, flaggy bedding, and limited doline development (Map 2d-e). The zone has well developed grikes and solution pans.

Location and lithology - The Pohara karst zone occurs as a northeast – southwest striking sequence of Oligocene Takaka Limestone (Figure 4.5). The Pikikiruna Fault running along the back of the limestone forms the south-eastern extent of the zone. In the Pohara and Takaka areas, the limestone runs from the ridge to the coast and forms sea cliffs and a series of connected limestone hills or knolls. Although the ridge follows the Pikikiruna escarpment, the limestone ridge, in some areas, is separated from the marble by insitu Tertiary sediments (Map 2d). Where the ridge terminates near Dry River, the limestone is separated from the marble by up to 500m.

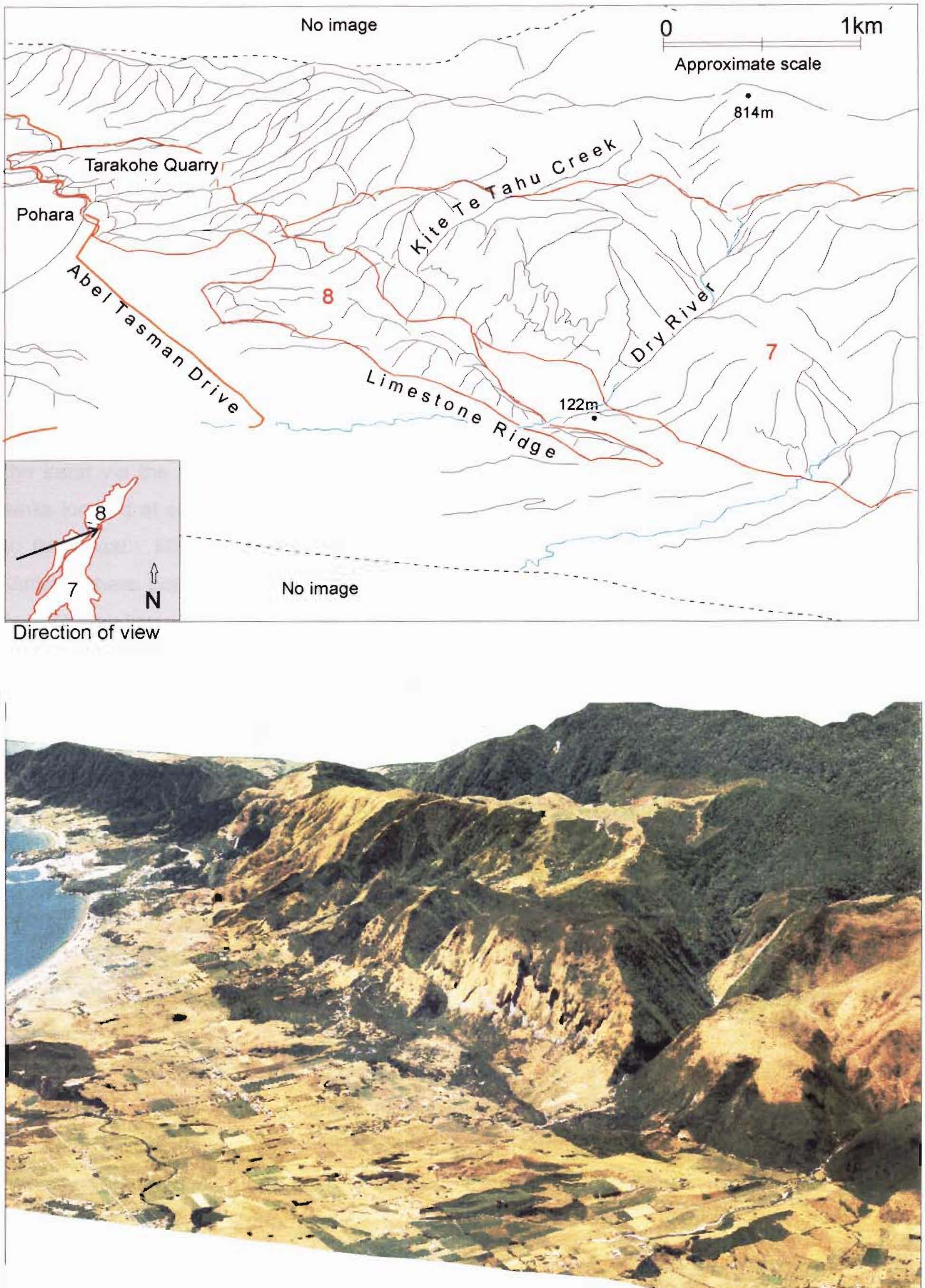


Figure 4.5. Showing East Takaka (7) and the steeply rising Pikikiruna Fault Escarpment that forms the eastern edge of the Takaka valley. The limestones of the Pohara zone (8) run adjacent to the scarp. (DEM model based on 20m contours, Land Information New Zealand. Crown Copyright Reserved. Aerial photos from Terralink, Copyright Reserved)

In contrast to the massive or fractured grey, blue-grey marble, the limestone outcrops comprise cream-grey flaggy, fossiliferous beds. Close to the Pikikiruna Fault the limestone beds are folded into a vertical orientation and form the ridge (or hogsback) evident in the Pohara, Clifton and Motupipi areas (Figure 4.5). Bedding in The Grove Scenic Reserve and Pohara and Tarakohe coastal areas is flat or gently dipping.

Because of restricted access, the Tarakohe area karst has not been field checked. An isolated occurrence of Takaka Limestone in the Upper Takaka area, observed in outcrop at Eureka Bend, and the karst immediate to the coast are not included in the Pohara karst zone.

Hydrology - Allogenic inputs to the zone are derived from runoff from the adjacent granites. Water from streams such as Gibson and Kite Te Tahu Creeks, and Dry River may infiltrate the karst via the Pikikiruna fault (Edgar 1998). Many of the smaller streams disappear in sinks located at or near the limestone contact. Some, such as Winter Creek, maintain flows to the coast. Minor allogenic inputs occur in areas such as Pohara Beach and Pohara Valley, where permeable sediments overlie the limestone. The limestone ridge and other outcropping limestone areas receive autogenic recharge. The Pohara and Tarakohe karst is free karst as waters can flow directly to the sea. There are numerous small ephemeral springs in the area. Local residents observe that the location or even presence of the springs can be disturbed by earthquake activity (Froriep, J., Haddon, D. *pers. comm.* 2002).

Karst landforms - Doline development in the Pohara zone is limited to occasional solution and/or alluvial dolines, which are mainly located on soil covered terrace surfaces or in remnant drainage channels. The dolines are often elongated in the direction of drainage. Dolines on the limestone ridge are orientated parallel to grikes. Field examination and aerial photographs (Haddon, D. *pers. comm.* 2002) indicate that elongated dolines and grikes appear to lie parallel to structural lineaments, which in turn strike oblique to the limestone ridge. Although not field checked, the Tarakohe area appears to host numerous collapse dolines.

An obvious small-scale feature of the limestone is the flaggy bedding. Styolite development is observed. Forms such as rinnenkarren and rundkarren seem more prevalent away from coastal areas. Common to the zone are solution basins, which develop on horizontal, often partially vegetated or moss covered, surfaces. The solution basins (or kamenitzas) are usually less than 20cm in length and < 5cm deep. Rillenkarren is not common.

Well-developed grikes are common in the limestone scarps and knolls. The grikes, in some instances, appear as corridors and are up to 10m in depth and vary in width from 10cm to several metres. The grikes contain concentrations of organic material and vegetation such as Nikau Palms and the extended roots systems of the epiphyte, Southern Rata.

Caves in the limestone are predominantly flat-lying or semi horizontal. Council Cave is one of the more renowned caves in the limestone (Worthy 1990). Cave or shaft entrances large enough to enter are common in the limestone outcrops.

Surficial cover - Non-calcareous soils derived from the allogenic input of material from the granites and Tertiary sediments dominate soil types in the Pohara area. Rendzic soils are noted, especially in grikes and where the limestone is exposed. Tertiary sediments and alluvial or coastal deposits cover many areas of the Pohara Limestone, forming flat, covered terrace surfaces.

4.4 Summary

As a result of the geomorphological mapping, which focused on identifying the type and distribution of surface landforms, soils, and hydrological systems, the study area has been subdivided into eight main karst landform assemblage zones. The karst zones: Kairuru, Takaka Plateau, Canaan South, Canaan North, Pikikiruna, Takaka Walkway, East Takaka and Pohara represent karst terrains in which similar geomorphological attributes are observed.

In order to explain the presence and distribution of the landforms, soils, hydrological systems, surface relief observed in the karst zones it is necessary to consider the relations between rock type, lithology and structure, hydrological systems, the availability of water, and temperature (Ford and Williams 1989). It is these factors that influence past and present day erosional processes.

CHAPTER FIVE – GEOMORPHOLOGY AND LITHOLOGY

5.1 Introduction

Analyses in this chapter aim to quantify observations made during the mapping regarding the frequency and distribution of landforms in the karst zones. The first two sections in chapter five provide the results of the geomorphological classification and lithological analyses. The aim of those sections is to:

- provide categorical data analyses on doline and karren type, and distribution, within the eight karst landform zones
- present the data from the fracture frequency, primary porosity and impurity analyses

Quantitative assessment of landform distribution are used to substantiate the delineation of the karst terrain into eight karst landform zones.

Discussions following on from the results assess the influence of lithological controls on small scale landform morphology and distribution

5.2 Objectives and rationale

The geomorphological classification and lithological sampling programmes were carried out in order to gather information on processes controlling karst development. The geomorphological classification is an attempt to quantify the relative influence of differing processes on the development of landforms within the karst zones. Lithological variation in the karst zones was assessed in order to understand the lithological influences affecting past and present erosional processes, and the resultant landform morphology.

The objectives of the geomorphological classification were to:

- provide a categorical inventory of landforms, particularly dolines and karren, the type and frequency of which can be utilised to establish the dominance of differing processes within each of the karst zones
- to aid in establishing a landform genesis model
- to assist in distinguishing natural and human induced environmental changes

Establishing the variation in lithological features, such as porosity, permeability and purity is fundamental to discerning the relations between erosional processes and landform genesis. Lithological and structural properties are of primary importance in determining karst landform morphology and development. For example, permeability or fracture frequency is the principal factor in determining accessibility of erosional processes to the carbonate rock while greater heterogeneity and impurity of the bedrock may limit many karren forms (Ford and Williams 1989, Sweeting 1972, Trudgill 1985).

The lithological sampling programme was designed to:

- evaluate lithological attributes in the karst zones
- assess whether variances (if any) in primary and secondary porosity or purity influence landform development in the karst zones

5.3 Geomorphological classification results

Dolines were selected for detailed analysis because recognition of the genetic class provides valuable information regarding the controls on development and evolution of vertical drainage. For example, the distribution and frequency of solution dolines is influenced by variations in the vertical permeability of the overlying surficial cover and the epikarst (Williams 1983). The main controls on landform development are discussed in Chapter six. Karren, because they evolve over time scales of tens to hundreds of years and are particularly responsive to changes in the soil or vegetative cover, were important in determining the short term or human impacted history of landform development (Chapter seven).

The geomorphological classification database is presented in Appendix A.

5.3.1 Dolines

Dolines are commonly regarded as the characteristic feature of karst topography (Ford and Williams 1989, Sweeting 1972) and the term doline is used here to mean any small to intermediate closed hollow in karst. The classes of dolines and the means of identification are outlined in Chapter 3.

Dolines are a widespread feature of the study area and are present at around 50% of the sites visited. Solution dolines are the most widespread class of doline in the study area, occurring at around 30% of the sites, while alluvial dolines are observed at a frequency of around 20%. Observed at only 6.5% of the sample locations, collapse dolines are the least common doline class in the study area (Figure 5.1).

Statistical analysis indicates that the spatial density or distribution of dolines is associated with the karst landform zones (Figure 5.1). The frequency of solution dolines varies in the karst zones (g test no. 21.46, df. 7, p 0.01). The partial g – values indicate that the greatest

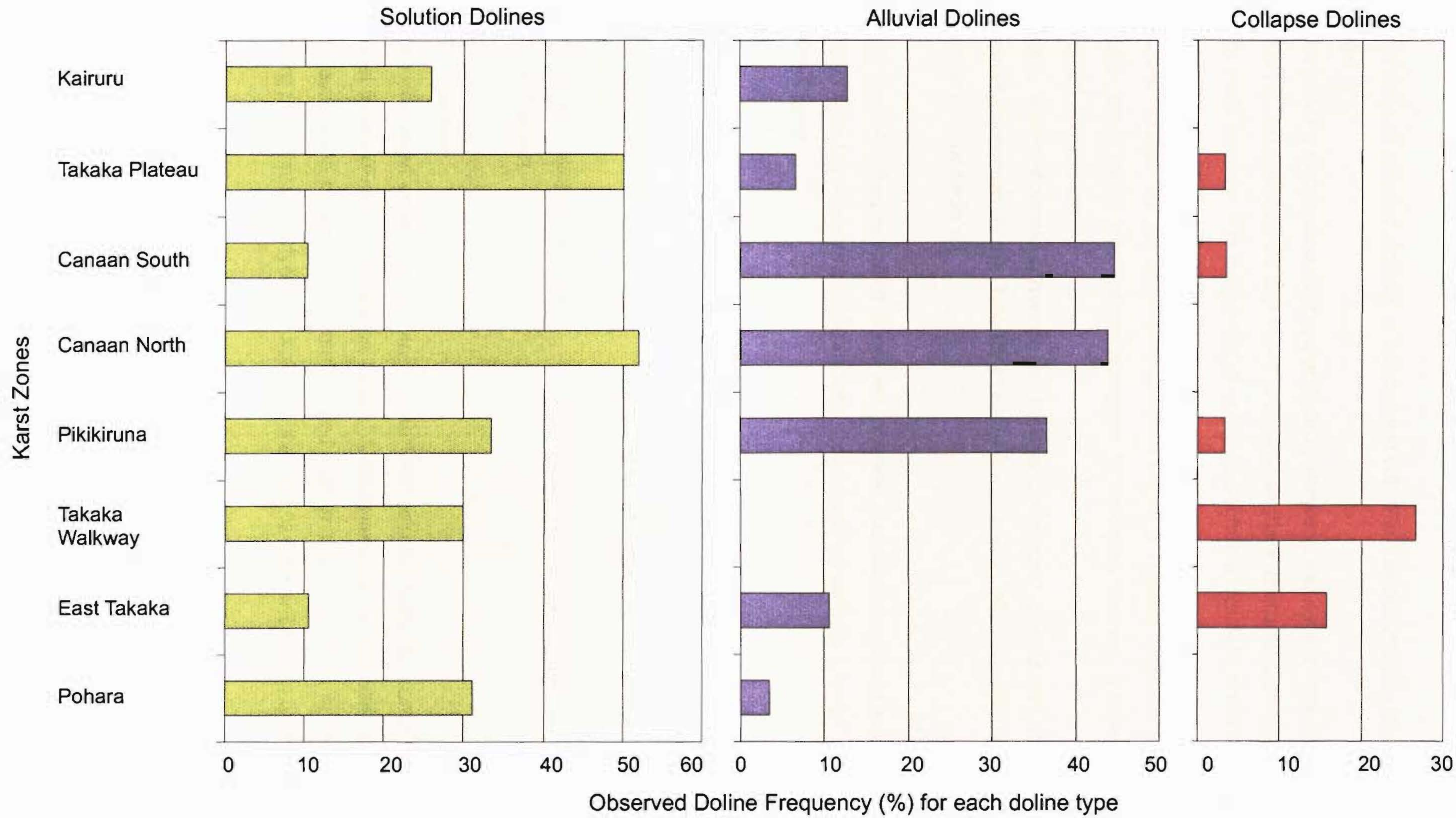


Figure 5.1. Results of geomorphological classification of genetic doline type in the karst zones. The graph illustrates the observed frequency of each class of doline in the karst zones. The results also show that collapse dolines are less common throughout the study area, while solution dolines are relatively widespread. In all cases the combined doline frequencies are less than 100% indicating dolines were not present at all sample locations.

occurrence of solution dolines is associated with the Takaka Plateau and Canaan North karst zones.
Alluvial doline distribution differs significantly between the karst zones (g test no. 47.86, df. 7, ρ 0.001). Alluvial dolines are more prevalent in the Pikikiruna, Canaan South, and Canaan North karst zones. The frequency of collapse dolines is spatially linked to the karst zones (g test no. 27.00, df. 7, ρ 0.001).
Collapse dolines are particularly associated with the Takaka Walkway karst zone. The East Takaka karst zone has larger numbers of collapse dolines relative to the statistically expected distribution.
Uvalas, where dolines converge to form a compound depression (Sweeting 1972), are especially common in the Takaka Plateau karst zone. Non-parametric statistical analyses are given in Appendix B.

Using the total frequency of observed dolines, including undetermined dolines, the doline density in the karst zones can be ranked, from most to least, as follows:

1. Pikikiruna
2. Canaan North
3. Takaka Plateau
4. Takaka Walkway
5. Canaan South
6. Kairuru
7. Pohara – Takaka Limestone
8. East Takaka

5.3.2 Karren

Karren are small scale surface and subsurface solution features comprising pit, groove and channel forms (Ford and Williams 1989). Understanding the genesis of the karren is useful in the evaluation of landform evolution and environmental impacts in the karst zones in that different processes and types of solution give rise to different karren types (Chapter 3).

Karren are common throughout the study area with a frequency of 69% observance over the entire karst landscape studied. Rundkarren are the most widely distributed small-scale solution forms throughout the study area occurring at 58% of all sample sites. Rinnenkarren are observed at a frequency of 32%, while rillenkarren are relatively sparse and are observed at around 6% of the sample sites (Figure 5.2).

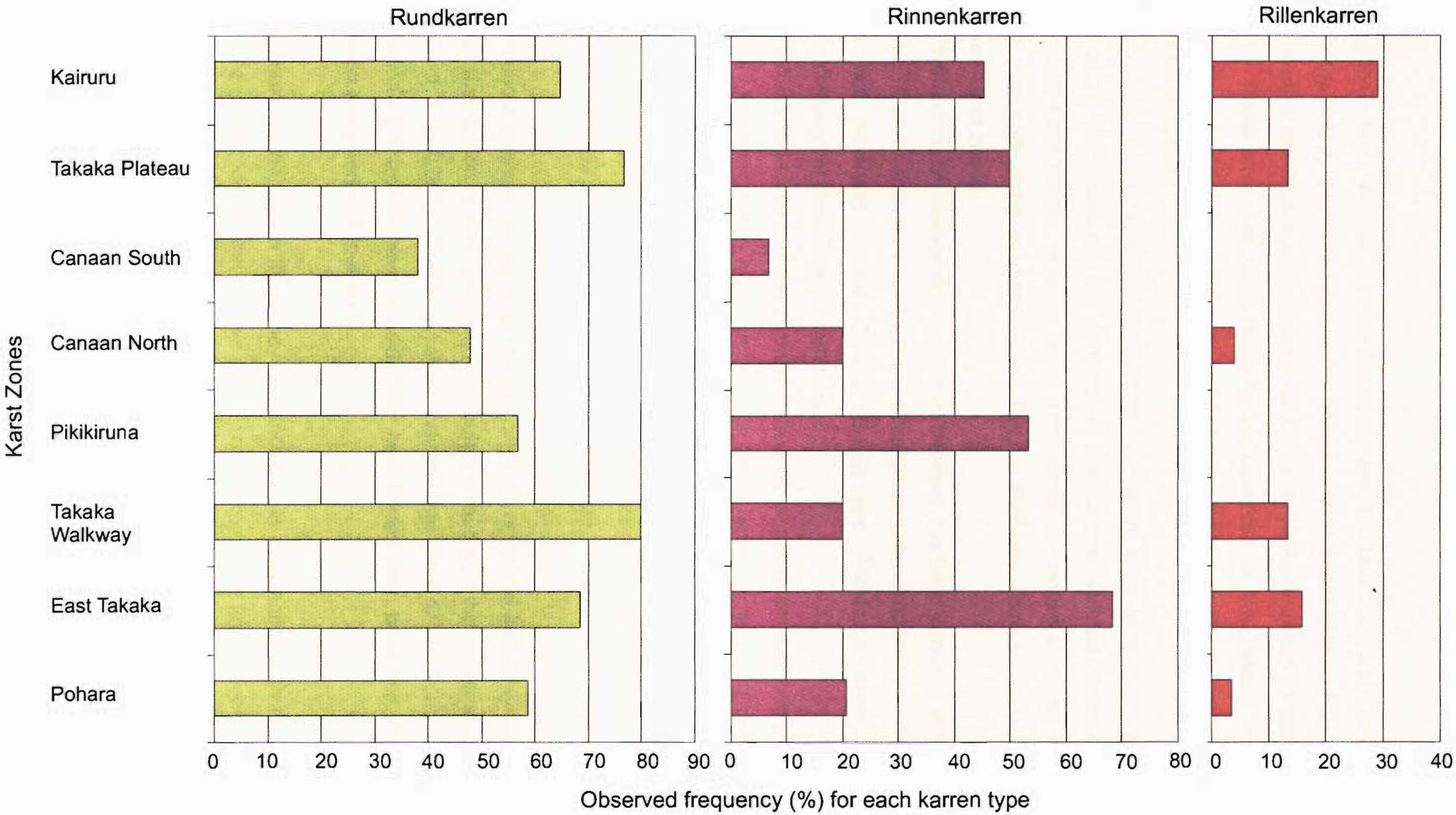


Figure 5.2. Results of geomorphological classification of karren type in the karst zones. The graph illustrates the observed frequency of the main class of karren in the karst zones. Rundkarren are the most commonly observed solution sculpture in all karst zones while the development of rillenkarren is relatively limited.

The g test values indicate that the frequency and distribution of rund- rinnen- and rillenkarren are not uniformly distributed across the karst landform zones (Figure 5.2).

The relative distribution of rundkarren is linked to the karst zones (g test no. 17.23, df. 7, p 0.05). Rundkarren are more likely to be observed in the Takaka Plateau and Takaka Walkway zones and least likely to be found in the Canaan South karst zone relative to the other karst zones.

The frequency of rinnenkarren is significantly different in the karst zones (g test no. 38.84, df. 7, p 0.01). Rinnenkarren are common in the Kairuru, Takaka Plateau, East Takaka and Pikikiruna karst zones. Results taken from partial g - values suggests that rinnenkarren is lower than statistically predicted in the Takaka Walkway, Canaan South, Canaan North and Pohara karst zones.

The distribution of rillenkarren also varies between the karst zones (g test no. 25.52, df. 7, p 0.001). Kairuru has significantly more rillenkarren than statistically expected. Rillenkarren were not observed in the Canaan South and Pikikiruna karst zones during the geomorphological classification sampling.

The Takaka Walkway has the highest frequency of grikes or kluftkarren while the Pohara – Takaka Limestone has a high number of solution basins or kamenitzas relative to the other karst zones and is the only area with styolite development noted.

Spitzkarren was seldom observed. Meander- and trittkarren were not observed during the geomorphological classification, but well-formed examples are located on the gently sloping, exposed surfaces of the Marble Acre karst pavement.

A statistical analysis of the total frequency of all observed karren types indicates that the karren distribution is not randomly distributed throughout the entire study area (g test no. 24.69, df. 7, p 0.001). Partial g values indicate that the Canaan South, Canaan North and Pikikiruna karst zones have considerably less karren than predicted. Non-parametric data analyses are given in Appendix B.

The results of the karren frequency classification, in conjunction with the fracture frequency data, were used to infer the relative density of outcrop in the karst zones. In both the fracture frequency measurements and the karren classification, records were taken only if rock was outcropping at the sample site. Therefore, the karst zones are ranked from predominantly exposed (free or half free) to mostly soil or sediment covered (covered) as follows:

1. East Takaka
2. Takaka Walkway
3. Kairuru

4. Takaka Plateau
5. Pohara
6. Pikikiruna
7. Canaan North
8. Canaan South

5.4 Lithological sampling results

Sampling and laboratory procedures are given in Chapter 3.

5.4.1 Primary Porosity results

Primary porosity for the Arthur Marble samples in all karst zones is comparatively consistent, with mean primary porosity values ranging from 1 – 1.75 %. The average primary porosity for all marble samples is 1.37% ±0.3. Values in the marble range from 0.43 – 4.08% (Appendix C).

Primary porosity in the Takaka Limestone is significantly higher and mean values are 3.26 %. Values range from 0.96% - 13.08% reflecting the lithological variations in the Takaka Limestone.

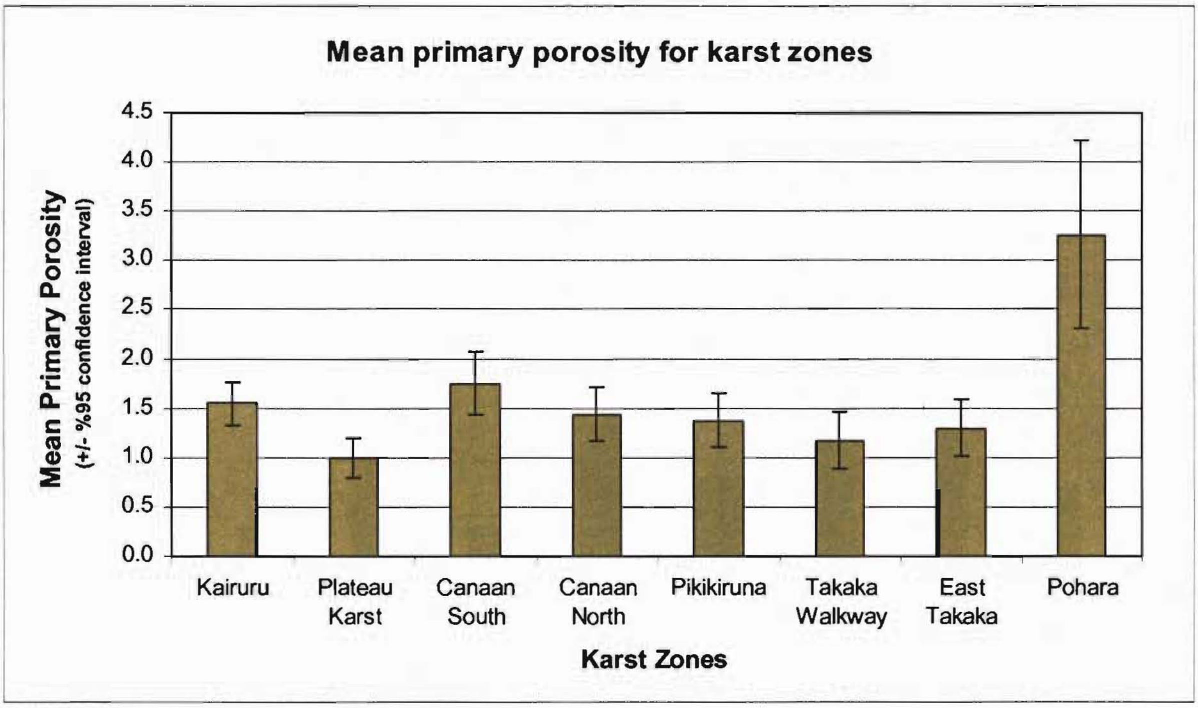


Figure 5.3. Mean Primary Porosity for the karst zones.

5.4.2 Grainsize

High rates of carbonate rock solubility are predominantly reliant on grainsize: the finer the grains the larger the surface area exposed to solution (Ford and Williams 1989).

Observations of whole rock grainsize made during porosity analysis indicate that the carbonate rocks in the field area comprise dense calcarenites (sand sized calcite grains) with a saccharoidal appearance. Dowling (1974) describes the Arthur marble as a sparry allochemical carbonate rock.

Grainsize was coarsest in the Kairuru karst zone. Grainsize in the marble appears fine to the west of the study area. Very fine textures were noted in the Takaka Walkway and East Takaka karst zones.

Grain size in the Pohara Karst - Takaka Limestone is more variable, with textural changes observed across bedding planes. The calcite grains are predominantly sand sized. Larger clasts and fossils (for example, scallop shells *Pecten*) were noted in some bedding planes.

5.4.3 Permeability (Fracture Frequency) results

The results of the fracture frequency sampling indicate that the density of structural features is not randomly distributed across the study area. Variations between karst zones are observed both in the field and in the statistical results. As observed in Figure 5.4, the Takaka Walkway Zone has significantly more structural features than other karst zones.

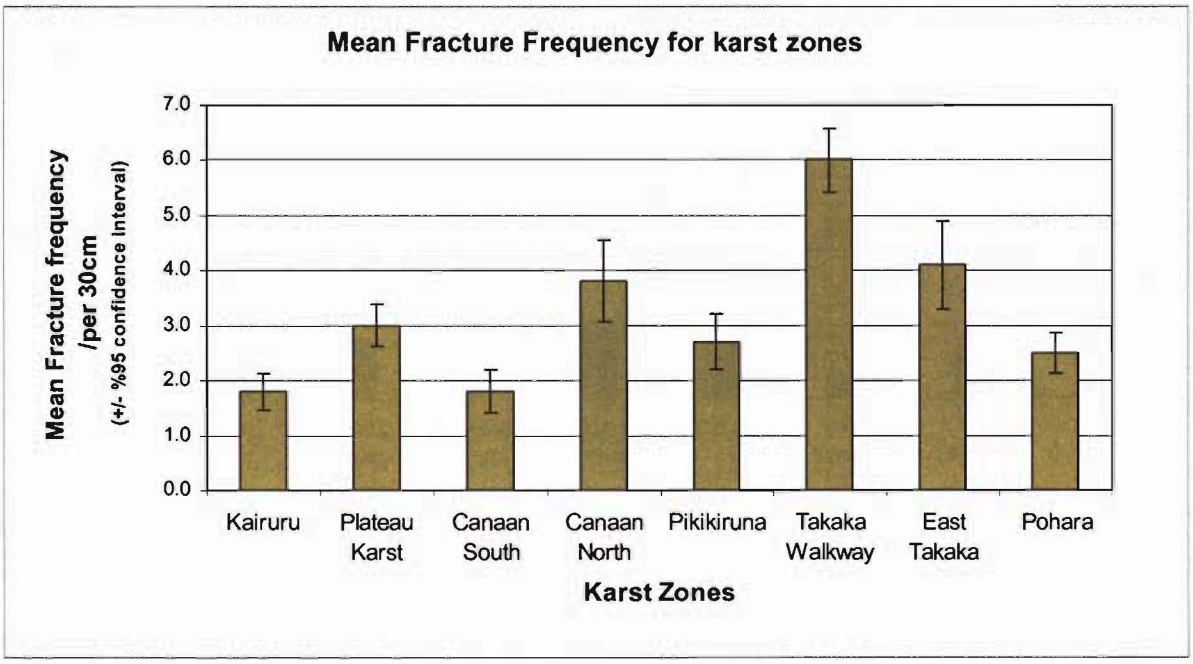


Figure 5.4. Mean fractures per unit length (30cm) for the karst zones.

The range of fracture frequency values is highest in the Takaka Walkway (0 – 21 fractures per 30 cm) and East Takaka karst zones (0 – 25 fractures per 30 cm). Canaan South and Kairuru, two of the easternmost karst zones are massive or have fewer structural features relative to the other karst zones, with values ranging from 0 – 7 and 0 – 8 structural features per 30 cm respectively. Summary statistics for the fracture frequency results are presented in Appendix C.

5.4.4 Lithological Impurities

The average purity of all the Ordovician marble rocks sampled is 94.1% ±0.6, with the Tertiary limestone being 93.4% ±0.6.

Analyses show that the percentages of insoluble material in bedrock samples are not randomly distributed throughout the karst zones. Unexpectedly, carbonate rocks in the Canaan South karst zone have significantly higher levels of non-calcium carbonate material than rocks in the other karst zones (see Figure 5.5.). Summary statistics for lithological purity are presented in Appendix C.

The range of values indicate that rocks in the Takaka Walkway and East Takaka karst zones have the least lithological impurities (up to 8.8 and 9.5 respectively). Marble in the Takaka Walkway karst zone with a mean purity of 98.3% calcium carbonate is very pure.

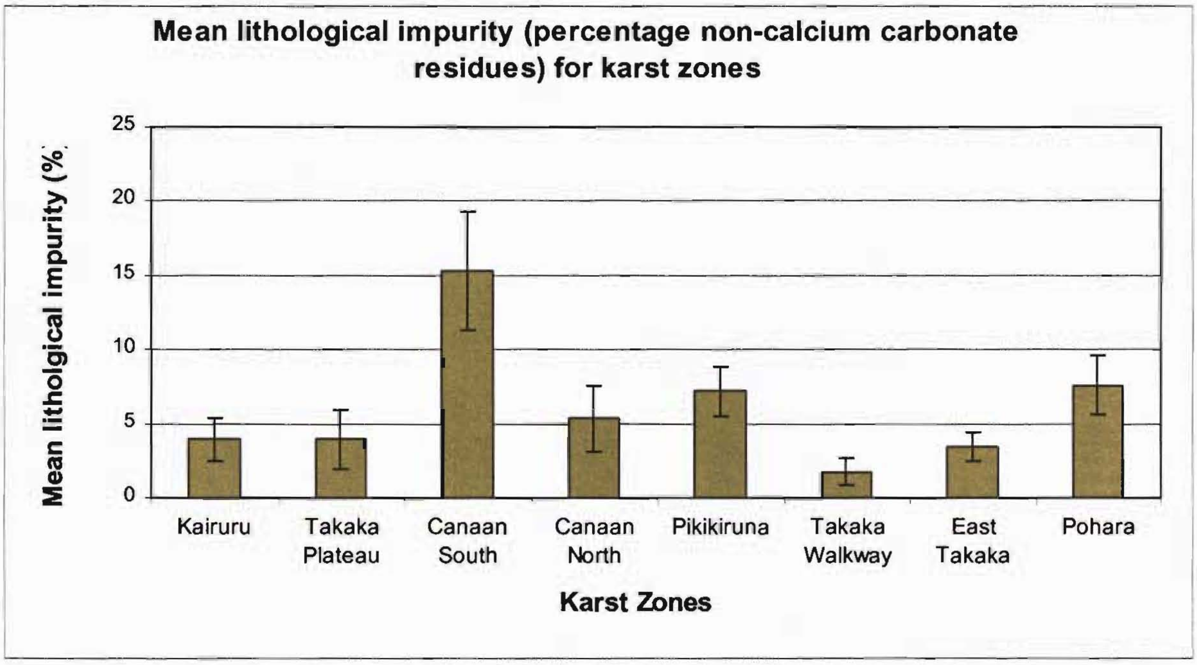
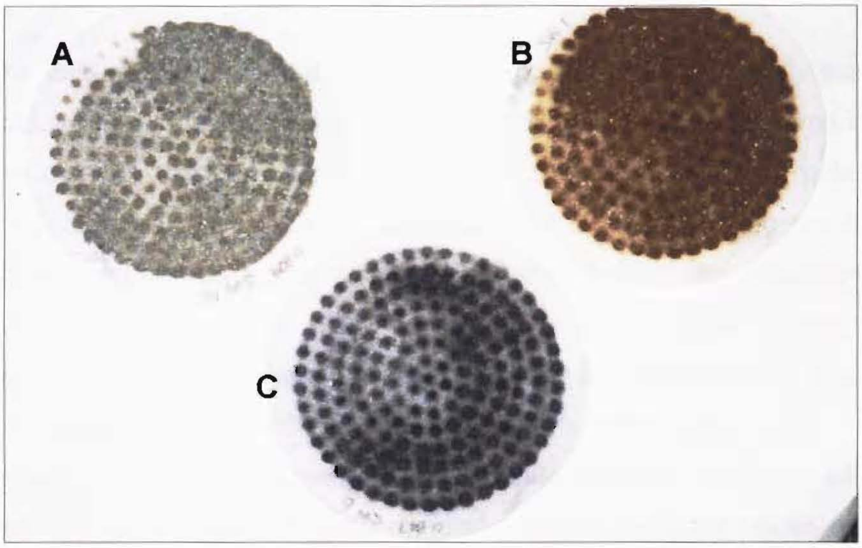
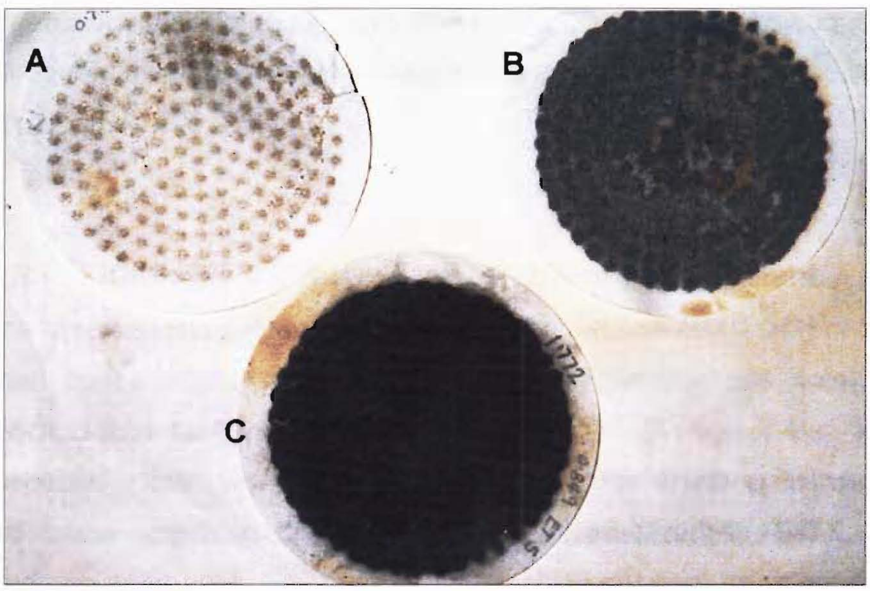


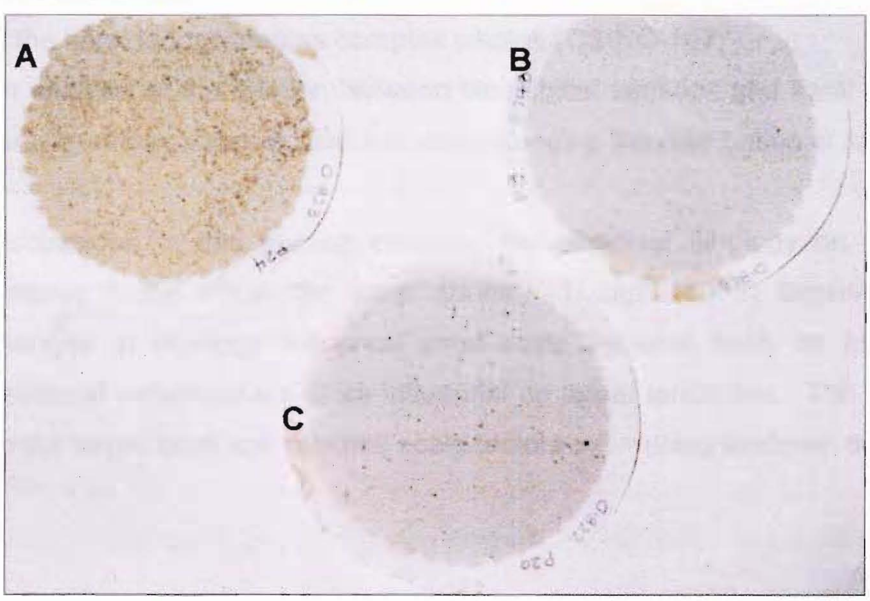
Figure 5.5. Graph of mean lithological impurity illustrating the significant non-calcium carbonate content of rock samples at Canaan South karst zone.



(a) Compositional Variation (from top left).
A. Quartz residues (marble)
B. Schistose residues (marble)
C. Carbonaceous residues (marble)
The most common residue is carbonaceous material, as shown in sample C.



(b) Rock Purity (from top left).
A. 99.3% Pure
B. 98.7% Pure
C. 95.2% Pure
The amount of carbon residues in the marble correlates to the colour: the more pure the marble, the whiter the colour. The most pure sample in this photograph (A) comes from Kairuru, where marble has been quarried for ornamental stone.



(c) Pohara Limestone (from top left).
A. Sandy limestone (87.1% pure)
B. Limestone (97.3% pure)
C. Argillaceous, dolomitic limestone (82.3% pure)

Figure 5.6. Samples taken from purity analyses, rocks were dissolved in acid allowing the residues to be assessed: (a) variation in insoluble residues throughout marble samples, (b) variation in amount of insoluble carbonaceous material in marble and (c) Takaka Limestone samples

The volume and composition of the residue material is closely associated with the observed colour of the marble and limestone. The grey to blue-grey marble specimens have larger amounts of graphite or carbon present, relative to the very pale or white marble in which impurities are almost negligible (Figure 5.6). The graphite residues are very fine grained, appear black to dark grey and have a sub-metallic lustre. Quartz sand, mica and occasional cubic crystals of pyrite (iron sulphide) are observed in varying quantities in the residual material. Euhedral crystals of pyrite (usually less than 2 mm), were more commonly noted in the Canaan South residue samples relative to other karst zones.

In contrast, the limestone has no graphite and the residues are tan coloured, clay sized particles of an undetermined mineral. Some residues under microscopic inspection form organic spherical or rod shapes and have high birefringence suggesting the material may be carbonate minerals such as dolomite that are not as readily dissolved in HCl acid (Shelley, D. *pers. comm.* 2003).

5.5 Lithological influence on landform development

The characteristics (type, scale, distribution, and development) of the landforms found in the karst zones arise in response to varying solutional and erosional processes and their reaction with the karst bedrock. Analysis of the lithological results is based on a process – response model where the morphology of the landform is seen as a response to the processes operating on the material involved (Trudgill 1985). The integrated study of landform zone attributes and the relationships between them are necessary to an evaluation of the karst landscapes as complex wholes (CSIRO 1977).

An analysis of the relation between lithological variation and karst type and frequency in the karst landform zones is useful in understanding the distribution of karst features.

Discussions in this section consider the effect of lithology on small scale or individual features found within the karst zones. Trudgill (1985) observes that very small-scale changes in lithology influence small-scale features such as karren, while larger scale structural variations are more influential on larger landforms. The following chapter focuses on the larger local and regional scale factors influencing landform development.

5.5.1 Porosity and grainsize

The marble, with mean primary porosity values of around 1.4%, is effectively impermeable to water. The primary porosity of rocks in the Takaka Limestone (3.26%) indicates that the limestone is also largely unable to transmit water without the development of secondary permeability. The mechanical strength of the limestone however, which is dependent on porosity and compaction (Jennings 1971) may be less than the denser and more impermeable marble.

The coarser grainsizes from northwest to southeast may correspond to the trend in metamorphic grade found in the study area. Increases in grainsize often occur in response to increasing metamorphic gradients. Paleozoic metamorphic gradients are at a maximum in the southeast and lowest to the northwest (Shelley 1991).

Porosity often shows a positive correlation with grainsize and both are important in controlling the type, form and regularity of some types of karren (Ford and Williams 1989). For example, the development of forms such as rillenkarren and trittkarren are inhibited in heterogeneous rocks (Ford and Williams 1989). The presence of well formed rillen- and trittkarren in the study area, indicates that the marble is of sufficiently high textural homogeneity and fine grainsize to support a wide range of small scale karst features.
Variations in grain size and sorting in the Takaka limestone and the prominence of horizontal or sub-horizontal bedding and styolites may explain the prevalence of karren forms such as kamenitzas and grikes in the Pohara karst zone. These forms are more commonly observed in relatively heterogeneous carbonate rocks (Ford and Williams 1989).

Primary porosity and grainsize in the carbonate rocks are relatively consistent over the study area, with the exception of the Pohara karst zone, indicating variations in texture play a minor role in explaining the differences observed in the marble karst landform zones.

5.5.2 Permeability/Structural features

Ford and Williams (1989) assert that structural features such as bedding planes, fractures and joints are of the greatest importance because they contain and guide most parts of the underground solution conduit networks that distinguish karst from all other systems. It is widely accepted that structural variations in karst rocks are one of the most fundamental factors influencing the morphology of karst landforms and the processes that shape them (Ford and Williams 1989, Trudgill 1985, Sweeting 1972).

Karstification of the Arthur Marble and Takaka Limestone is reliant on the enlargement of openings and conduits along structural features. The karst zones, representing covariance between landform characteristics, are in part a result of differences in the nature, frequency and pattern of penetrable joints, fractures, faults and other planes of weakness throughout the study area (Jennings 1971).

The prevalence of collapse dolines, grikes and other karren forms, autogenic drainage, and rendzic soils in the Takaka Walkway zone is largely attributable to the dominance of structure in karst development. The high frequency of structural features in the Takaka Walkway caused by Paleozoic brecciation (Shelley 1991) and tectonic stresses derived from the Pikikiruna and other faults has led to an increased permeability relative to other karst zones. The high density of structures, and large scale faulting increases the number of solution pathways available for exploitation by solutional processes and leads to the development of non-point source, diffuse autogenic drainage and thus, more uniform epikarstic percolation (Ford and Williams 1989). The more regularly spaced percolation pathways in the Takaka Walkway area have resulted in limited solution doline formation and less surface relief. The small basins, common to the Takaka Walkway karst zone, are not dolines in the true sense but are depressions caused by the removal of interbedded cleaved mudstones. The contacts between the clastic rocks and the marble appear to provide a focus for drainage and localised sediment removal.

The effect of limited structural features on karst development is observed in the Takaka Plateau karst zone, which is similar to the Takaka Walkway in that it is also dominated by karren development, autogenic drainage and rendzic soils. Relatively limited structural features in the Takaka Plateau zone have promoted the development of relatively convergent autogenic drainage and a subsequent increase in surface relief and forms such as solution dolines and uvalas. Ford and Williams (1989) do note however, that the idea of convergent – uniform drainage in landform evolution is complicated by other non-structural factors such as vegetation and surficial cover that also operate to focus denudational processes.

Increased fracturing leads to the preferential formation of collapse dolines and grikes, both of which are abundant in the Takaka Walkway zone (Figure 5.7). The increased frequency of solution conduits, promotes grike or kluftkarren formation and also, causes a reduced strength of cavern roofs thus, favouring the development of collapse dolines or tomos (Sweeting 1973). The larger than expected numbers of collapse dolines observed in the East Takaka karst zone are likely to reflect the localised increase in structural discontinuities caused by proximity to faulting and intrusions. Figure 5.7 illustrates the influence of fracturing and jointing on karren development.

Figure 5.7. Effect of permeability on small scale solution sculpture. The more fractured surfaces (a) and (b) disrupt surface runoff restricting the development of rills and runnels (Takaka Walkway). Grikes (c) are more common in fractured bedrock (Takaka Walkway). The solutional enlargement of joints is seen in this outcrop at Kairuru (d), which is sufficiently massive to support rinnenkarren. The most well-developed rinnenkarren (transitional to spitzkarren) are found on massive outcrops (e).

Climatic factors also contribute to collapse doline formation: wetter and more seasonally affected areas often have larger numbers of tomos (Sweeting 1973). The Takaka Walkway and East Takaka areas are exposed to the prevailing westerly rainstorms and winter frosts, common at higher altitude, may increase the prevalence of freeze-thaw cycles that encourage bedrock fissuring.

The closely jointed and highly permeable nature of the bedrock also operates to limit the variety of karren developed. Rinnenkarren, which require massive or homogeneous outcrops are limited in the Takaka Walkway zone. Rillenkarren, which is a much smaller form, is only observed in those areas of the zone where the fracturing is sufficiently widely spaced to allow runoff.

The prevalence of well-developed and relatively large grikes (up to 2-3m wide and up to 10 deep) in the Pohara karst zone is most likely because of the nature of the limestone, which is well-jointed and well bedded (Ford and William 1989). The grikes, that are large enough in some areas (such as the Grove) to comprise corridors, appear to be aligned parallel to local structural lineations, indicating the predominance of structural features in the development of the karst.

5.5.3 Impurity

Direct comparisons between laboratory solubility and susceptibility to erosive processes in the field are complicated by other lithological factors such as grain size and textural heterogeneity. But in general, dissolution rates in carbonate rocks are fastest where the rocks are between 86 - 100% pure (Ford and Williams 1989). The carbonate rocks in the karst zones (mean purity of 94%), with the exception of Canaan South karst zone lie within this range.

Most of the rocks sampled in the Canaan South karst zone are greater than 15.3% impure. The lithological samples analysed for the Canaan South karst zone, although impure and often very sandy in appearance, are compositionally greater than 50% calcium carbonate and thus, are still termed as limestones. The prevalence of quartz sand at a volume greater than 10% (Figure 5.8) indicates that much of the carbonate rock in the area is a sandy limestone. Several samples in the Takaka Limestone also comprise impure limestones (refer to Figure 5.6)

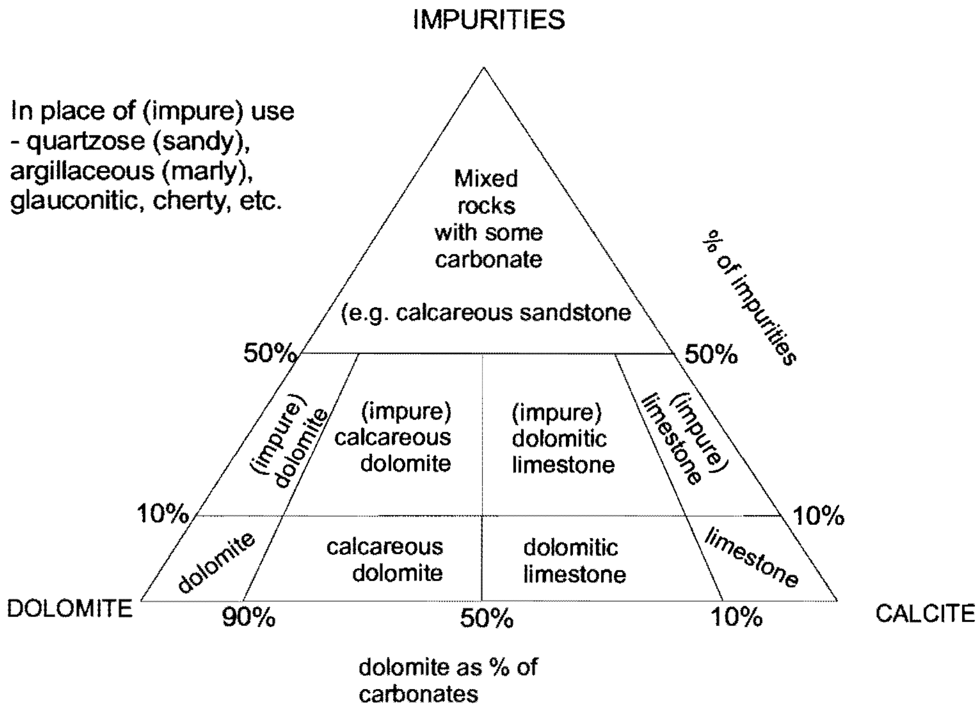


Figure 5.8. Limits for mixed rocks by Leighton and Pendexter 1962. (cited in Jennings 1972)

The high percentages of insoluble material in the Canaan South karst zone may have implications for conduit formation and therefore, karst development and the presence of the Canaan polje. In general the development of karst is limited when the volume of insoluble material (such as sand and clay) is greater than 30% (Ford and Williams 1989). The availability of relatively larger amounts of insoluble material (up to 44%) may limit the development of solution pathways and/or cause sedimentation of existing conduits. Insoluble residues causing clogging of or hindering conduit formation can restrict the amount of sediment removed via cave systems. The gravels forming the alluviated valley floor indicate that much of the overlying sediments in the Canaan South karst zone are derived from the surrounding granitic catchments, but the relative contribution of allochthonous or autochthonous sediments in causing inundation of the Canaan South karst system is not easily distinguished.

A further complicating factor in dissolution of the Canaan karst rocks is the relatively common presence of pyrite. The presence of iron sulphide is important in karst rocks as reactions in the karst system lead to the formation of insoluble limonite and sulphuric acid. This acid then corrodes the carbonate rock to form soluble calcium sulphate and carbon dioxide that in turn promote increased corrosion of the rock (Ford and Williams 1989). The extensive sedimentary deposits and the subsequent lack of aerially exposed surfaces, and the limited number of solution pathways, may restrict the effectiveness of pyrite in enhancing solubility in the Canaan South rocks.

5.6 Summary

There are notable differences in the genetic types of dolines and karren and their distribution in the eight karst zones and thus, the processes operating to form the different karst assemblages are also different.

Lithological influences particularly fracturing and jointing, which lead to an increased permeability of the otherwise impermeable bedrock, can account for some of the differences in distribution and type of relatively small-scale karst features observed in the karst zones. Karst systems and landforms in the Takaka Walkway zone, for example are highly controlled by structure and increased fracturing. Lithological heterogeneity, structural lineations, and gently dipping bedding planes are likely to explain the prevalence of grikes and kamenitzas in the Pohara zone.

Lithological factors such as purity, porosity and grainsize, although important to facilitating, or limiting some erosional processes, do not vary significantly over the scale of the karst zones and therefore, have a limited influence on the variations in landform morphology and distribution noted between the karst zones.

CHAPTER SIX – KARST EVOLUTION AND LANDFORM DEVELOPMENT

6.1 Introduction

Landform development in the Takaka and Riwaka karsts reflects the interactions between lithology, geology, and climate. These factors influence, or act to vary, the activity of landforming processes operating on the carbonate rocks over time. Discussions in the previous chapter indicate that although structure is an important control on landform development in the karst zones (especially in the Takaka Walkway zone) lithological variations do not account for the majority of differences noted throughout the study area.

This chapter examines the importance of other variables on karst development and includes:

- A review of the regional history of karst development, focusing on climate and tectonic controls.
- A summary of the main landforming processes and the relative influence of those processes in the different karst zones.

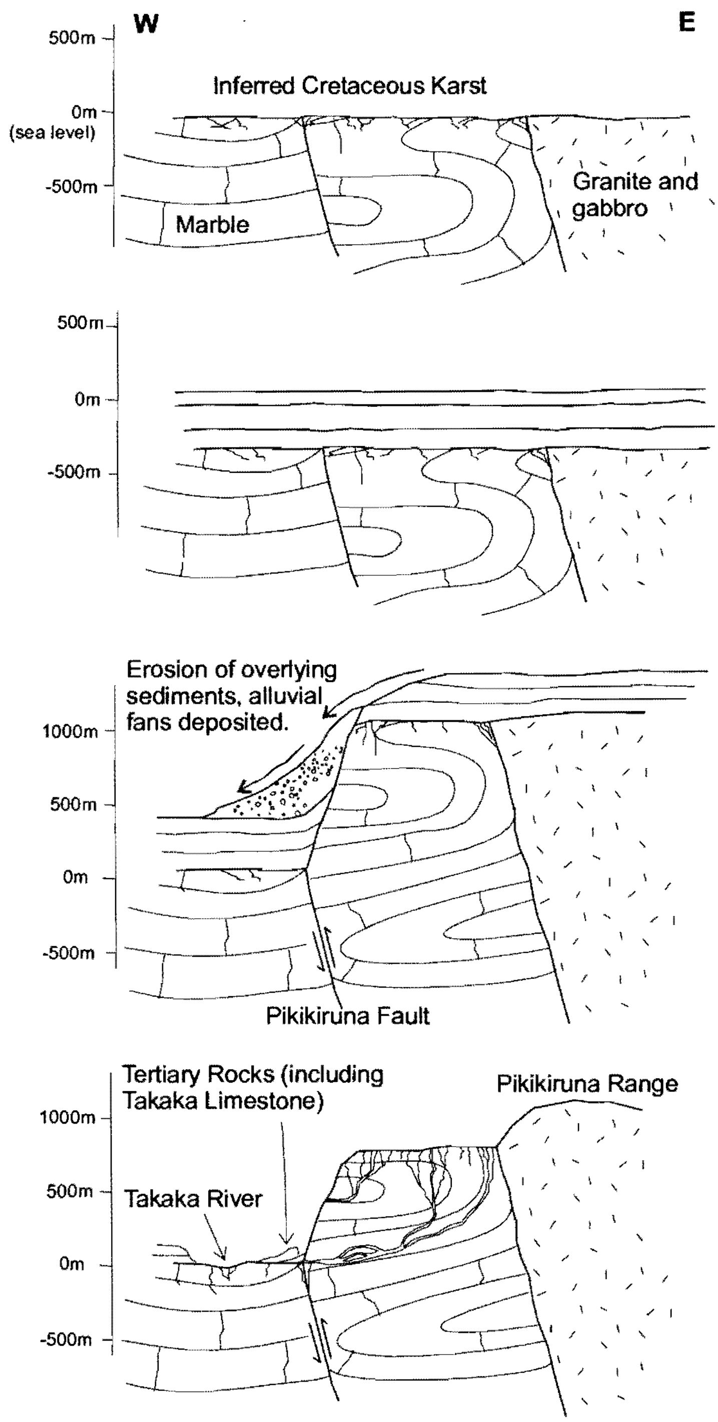
6.2 History of karstification in the Riwaka and Takaka karsts

Although the karst rocks were formed some 400 million years apart, much of the karst present in the marble and the limestone is of a comparable age and reflects Late Tertiary - Quaternary karstification. Deformation of the entire Tertiary sequence indicates that the earliest ruptures on the Pikikiruna Fault and thus, exposure of the present karst systems, occurred around 15 million years ago after deposition of the Tarakohe Mudstone (Edgar 1998). A summary history of karst development is outlined in Figure 6.1.

6.2.1 Geological influences on karst evolution

The history of karst landform development in the marble karsts is complicated because the present landform assemblages are likely to comprise elements of active and inherited (or resurrected) karst components. Jennings (1971) defines inherited landforms as those formed by past processes and in which conditions have now changed, and resurrected landforms as those occurring due to the exhumation of a previously buried karst landscape.

It is likely that at least one period of karstification preceded the existing Takaka - Riwaka and Pikikiruna karst systems. The unconformity between the Tertiary sediments and the underlying marble basement rocks is used to infer karstification of the marble surface in the late Cretaceous.



(a) ~65-55 million years ago. Peneplanation and inferred exposure of marble to surface.

(b) ~55 - 25 mya. Marine transgression and deposition of Tertiary sediments (including the Takaka Limestones).

(c) ~25 - 2 mya. Tectonic movement on the Pikikiruna Fault occurring in the Late Tertiary. New base level formed rejuvenating denudation and incision. Takaka Limestone folded into vertical attitude. Tertiary sediments overlying marble eroded, and subsurface drainage systems develop.

(d) Continuing to present day. Vertical denudation of marble plateau, continuing evolution of karst systems and landforms.

Figure 6.1. Idealised summary of karst evolution, showing the development of the karst systems from the Early Tertiary to the present day.

The marble, prior to burial by the Tertiary sequence, comprised part of a regional peneplanation surface and would presumably have formed a land surface (Figure 6.1.a), thus the rocks were exposed to solution and karst development. Mueller (1991) and Dowling (1974) also propose that a paleocave system was active during peneplanation but note that any former karst system would have been highly modified by reactivation of the present karst systems in the Late Tertiary – Quaternary.

Deposited 35 - 25 million years ago, the Takaka Limestones originally comprised part of the Tertiary sequence covering much of the Takaka area (Figure 6.1.b). Karst development in the Takaka Limestones is somewhat simpler than the Arthur Marble karsts in that the present karst systems may be considered as active (Jennings 1971) because the natural processes operating in the present are largely the same as those responsible for shaping the landforms in the past. Erosion following uplift and folding (Figure 6.1.c), exposed sections of the limestone sequence, which are now visible throughout the Takaka Valley floor, including those outcrops at Paynes Ford, the Grove, Pohara and Tarakohe. Those limestones adjacent to the Pikikiruna fault were folded into near vertical attitudes as seen in the outcropping 'hogsback' ridge from Tarakohe to Motupipi – Clifton.

The Pohara karst zone is distinct from the marble karsts in that sea level changes have affected the base level considerably and coastal processes have operated to produce distinct karst landforms, particularly at the intertidal zone where corrosion and corrasion are enhanced (Ford and Williams 1989, Trudgill 1985). Coastal karst forms, such as notches bio-eroded by marine organisms are beyond the scope of this study.

Because the Takaka limestones are located close to sea level and the maximum height above the present sea level is less than 150m, Quaternary oscillations in sea level have resulted in significant changes in the watertable. Negative base level changes are reflected in the coastal cliffs, formed because of a loss of support and increased basal erosion (Ford and Williams 1989).

Denudation of the Pikikiruna Range and marble plateaus appears to have proceeded rapidly compared to the limestones in the Takaka Valley. Removal of the entire Tertiary sequence from the newly formed plateaus and range gives some indication of the level of erosive activity occurring after uplift (Figure 6.1.c). Although theoretical, the formation and subsequent removal of an Oligocene karst system on the Pikikiruna Range provides an indication of the relative speed with which processes operated.

Fundamental to the development of the Ranges and plateaus are the hydraulic gradients produced by the change in relief from the marble uplands to the Takaka and Riwaka Valleys (Figure 6.1.c). The hydraulic heads resulting from a >1km change in altitude would have greatly accelerated denudation of the overlying Tertiary cover (by mechanical erosion) and the marble bedrock (by solution). Rejuvenation of erosional activity and the increased potential for dissection following tectonic uplift (Williams 1987, Trudgill 1985) is reflected in (a) the presence of deeply incised gorges, (b) the abandonment of upper level, phreatic cave stream systems as the aerated (vadose) zone above the water table is enlarged and (c) lowering of the permanently waterlogged (phreatic) area into less karstified rock (Figure 6.1.d).

Evidence from seismic data indicates that maximum movement on the Pikikiruna Fault occurred during the Late Miocene - Pliocene period, from around 15 to 2 million years ago (Ravens 1990, Thrasher 1989). Ravens (1990), because of a lack of deformation in the overlying Quaternary gravels, constrains the most recent fault movements in the area to the Late Pliocene. Although initial results of speleothem dating of Takaka Valley cave deposits, by Williams (1982), proved inconclusive, Williams (1987) indicates that minor uplift and incision continued through to the Late Pleistocene. A review of tectonic activity in the Takaka area may be required since a recent study of glaciation in the Takaka Valley by Shulmeister et al. (2003b), which suggests deglaciation of the main Takaka Valley occurred around 15 000 years ago. By inference, many of the gravels in the Takaka Valley were deposited after this event. These deposits are therefore younger than previously considered and cannot constrain post Pliocene fault movements.

Remnants of paleodrainage features suggest that relatively large rivers were active prior to breaching of the Tertiary caprock. Features such as windgaps in the Canaan and Wainui Saddles, remnant terraces several hundred metres above present aggradation surfaces, and the presence of fluvial deposits in areas far removed from contemporary drainage systems are used to provide evidence of a formerly extensive surface drainage system.

The earlier surface drainage patterns are reflected in the present location of karst valleys. Although enlargement of many karst valleys in the study area are a result of corrosion and corrasion after karstification (Dowling 1974), the valleys represent former surface channels. The karst valleys mark the transition from fluvial erosion to sub-aerial solution as the previously surface waterways were abandoned in favour of vertical drainage through the marble.

Figure 6.2 gives a possible reconstruction of early river systems, and indicates that the head of the Wainui River Valley may have been located southwards of its present location, which is marked by a windgap at the Wainui Saddle (Figure 4.3).

The linear nature and similar orientation of the Wainui and Canaan North Valleys indicate that tributary flows to the Wainui River may have flowed via Gorge Creek. Flows may also have extended from the Canaan area to the Holyoake Valleys prior to uplift and development of the plateau surface (Figure 6.2). Gorge Creek, observed from the Harwood's Hole lookout is marked, high on the valley sides, by a transition from a wider valley to an incised steep 'v' shaped profile. The change in valley profile may indicate the change from planation to incision following uplift.

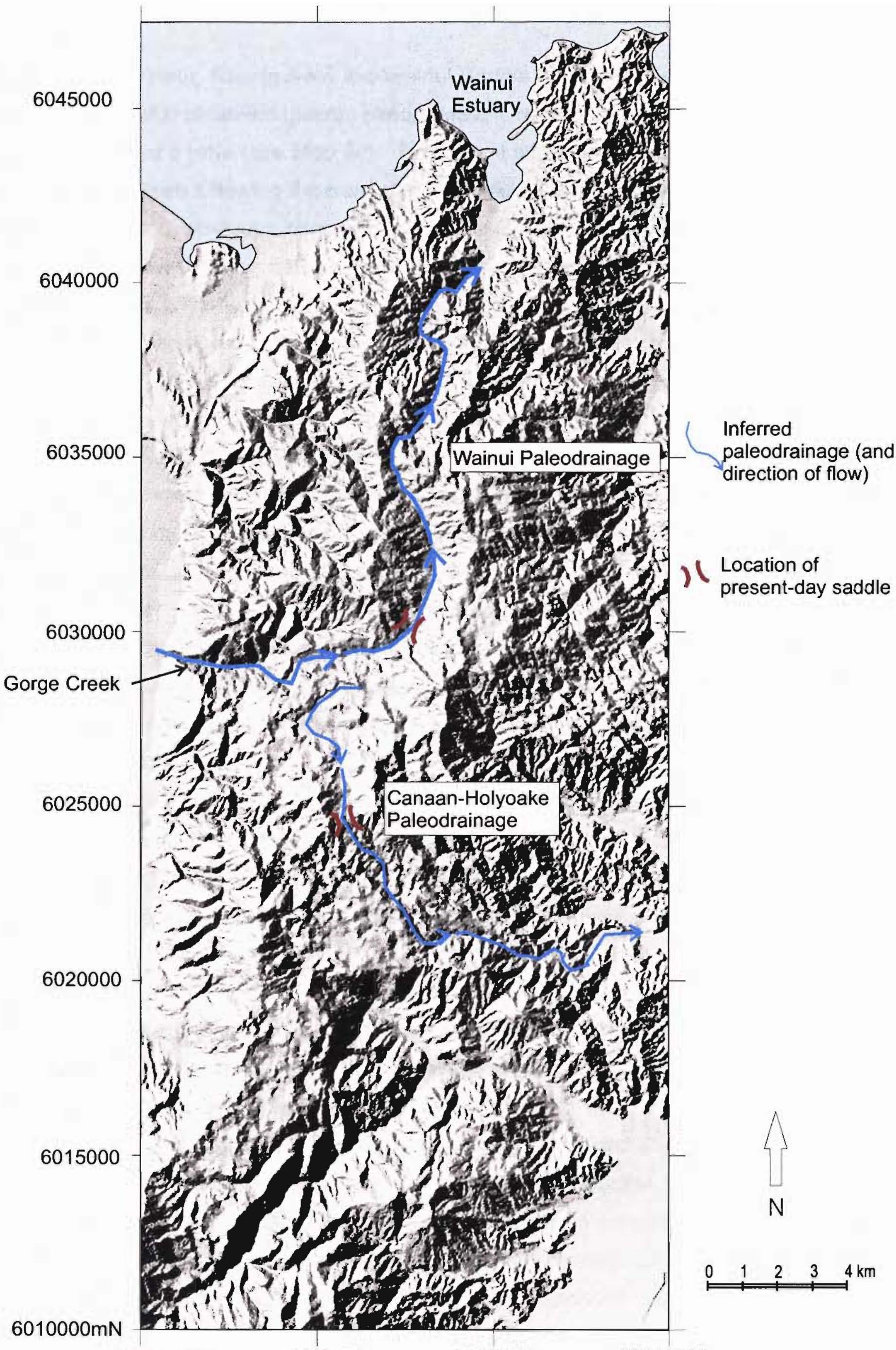


Figure 6.2. Inferred reconstruction of early river systems, occurring prior to uplift and karstification. The direction of drainage may have been reversed after uplift, the windgaps (marked by the present-day saddles) indicating the point at which the drainage was captured or reversed.

A later stream system, flowing from the Wainui Saddle to Harwood's Hole is confirmed by Williams (1987), who observed granitic stream gravels resting on the sides of the karst valley leading to Harwood's Hole (see Map 2c). This recent stream may indicate that the drainage network was reversed following the truncation of an earlier north-flowing waterway. Both the Wainui and Canaan windgaps occur close to karst – granite contacts indicating the larger historic drainage system was likely to have been captured and the channels reorganised by karst development. The large estuary in Wainui Bay, the size appearing anomalous to the current catchment area, may attest to a previously larger catchment or tributary.

Breaching of the overlying impermeable Tertiary cover during the Late Pliocene-Early Pleistocene activated the development of new protoconduits in the marble and possibly reactivated earlier karst systems. Although complicated by the lowering of surface channels during removal of the Tertiary sequence, part of the present karst system may be imprinted onto earlier karsts by the contemporaneous surface lowering, or inheritance, of former drainage systems.

Faults and other structural features would have allowed for the rapid exploitation of transit routes for water through the marble massif. The importance of major structures in providing early accessibility of water to the karst rocks is reflected in the correlation of resurgences and sinks to mapped and inferred faults. Of particular interest are those sinks and resurgences, such as the Summit and Sawmill Sinks, which have significant morphological expression. Although faulting may be responsible for the increased topographic expression, the relatively high escarpments associated with the fault-related sinks and resurgence indicates that these features may have formed earlier than those hydrological features in the study area with little or no surface relief (Sweeting 1973).

As expected, once throughput and output connections through the marble developed, solution would have been the dominant geomorphic process. Approximately 80% of this solution occurs in the near surface or epikarstic zone and thus, much of the solution is reflected in surface lowering of the bedrock surface (Williams and Dowling 1979). Dowling (1974) in a study of solution rates in the Riwaka Basin noted that the rate of marble removal is equivalent to 5772 tonnes/yr/km^2 and that if climatic changes were disregarded, over 600m of carbonate rock may have removed from the exhumed peneplanation surface. Assuming the peneplain formed a predominantly uniform surface, inferences about surface denudation can be made using changes in relief on the karstic uplands (Dowling 1974). The highest peaks in the Canaan area, formed in non-karst rocks and thus not affected by solution, are around 1100 – 1150m (Mt Evans 1156m). The height of the Canaan Downlands at 750m indicates that at least 400m of marble has been removed, estimations of surface lowering elsewhere in the study area and Arthur Ranges (Dowling 1974) show similar levels. Long-term chemical corrosion is reflected in the surface karst landforms. The main karst landforms, namely dolines, karren, caves and valleys, are erosional (Ford and Williams 1989), indicating that solutional processes were and are operating to remove rock mass.

6.2.2 Quaternary climate change

Climatic conditions, such as the changes in precipitation and temperature associated with glacial expansion and retreat, affect rates of denudation and the type of denudation (Lauritzen 1993). Rates of chemical denudation are primarily influenced by the availability of water: the wetter the conditions, the higher the rates of solution (Ford and Williams 1989). Of secondary importance is the aggressiveness of the solution (Goudie 1995). The effects of aggressive waters, which are largely related to the presence, or absence, and type of surficial and vegetative cover are discussed in the following section.

Dowling (1974) noted that while solutional denudation rates in the Riwaka Basin (99 $m^3/yr/km^2$) are comparable to those in the Waitomo karst (73 $m^3/yr/km^2$) and on the West Coast (126 $m^3/yr/km^2$), when compared to other karsts worldwide, the rates are high. The availability of water is significant in a humid region like New Zealand with high annual precipitation. Evapotranspiration rates are generally low, particularly where the waters can rapidly percolate underground (Dowling 1974). A review of climate changes indicates that the current moist, temperate conditions have prevailed throughout the Holocene (last 12000 years). That climatic conditions have been relatively stable in that period is inferred by Shulmeister et al. (2003a) and Moar (1971) from studies of pollen records and the associated vegetation changes.

Climatic conditions prior to the Holocene are generally regarded as cyclic, episodic cooler glacial event alternating with warmer interglacial conditions (Suggate 1990). Solution was most intense in the wet, mild interglacial periods (Dowling 1974). While drier conditions are often associated with glacial periods, the scale of moisture change is not well understood (Shulmeister, J. *pers. comm.* 2003). Reduced rates of solution, produced under possibly drier conditions, may slow down rock dissolution but do not necessarily alter the style of karst development (Ford and Williams 1989). Changes in the style of karstification may however, occur during glacial periods as a result of lower temperatures and a predominance of freeze - thaw processes. The mean annual temperature at Riwaka, near sea level, is 12.3°C with a mean annual temperature variation of around 11°C. On the uplands the temperatures are 4-5°C lower. During cooler glacial events, the temperatures are further reduced by about 3-5°C (Burrows 1979, 1977), indicating that the mean annual temperature at altitude during glacial periods can be conservatively estimated at around 4°C. With temperatures more commonly oscillating around 0°C, freeze-thaw processes may have replaced solution as the dominant geomorphic agent. While there is a lack of evidence (possibly because of the removal of the surface debris by subsequent denudation) for the widespread occurrence of freeze-thaw processes, the scree slopes, common in the gorges located on the Pikikiruna Fault Scarp and on the Arthur Ranges (Dowling 1974) may reflect the periodic dominance of mechanical weathering.

6.2.3 Summary of karstification

The commencement of karstification of the current karst systems corresponds to movements on the Pikikiruna Fault and the resultant exhumation of the marble and exposure of the limestones. After tectonic uplift, Tertiary sediments covering the Arthur Marble and Takaka Limestone were eroded, and surface waterways established on the overlying non-karst sediments were progressively captured underground by the developing karst systems. Solutional denudation, which is accelerated by high precipitation and uplift, is the dominant landforming process. Climatic oscillations in the late Pliocene and Pleistocene have resulted in changes to the rates of solution and the dominance of either chemical or mechanical erosion.

Although changes in the geological history and climate are useful for understanding the evolution of the karst landscape as whole, these factors do not vary greatly over the scale of the karst zones. Thus, other factors control development in the karst zones.

6.3 Influence of differential erosion on karst evolution

Although solution and mechanical erosion are the main processes acting on the karst rocks, with neither working in isolation from the other (Williams 2001), it is the relative influence and varying rate of these processes in the different karst zones that is fundamental to assessing the different geomorphological attributes in the karst zones (Trudgill 1985). Differential erosion, or the spatial variation in processes and rates, operates to erode some part of the rock mass more than another resulting in differing landform development (Trudgill 1985).

The results of the mapping and the geomorphological classification indicate that the main controls on process variation are (a) hydrological systems and the interrelated sediment and soil cover, which influences the geochemical evolution of the waters (Williams 2001), and determines the relative dominance of fluviokarst features or doline karst development and (b) gradient and relief, which controls topography, drainage and hydraulic heads (Map 1). Table 6.1. summarises the inferred associations between the landform attributes and the predominant controls on karst evolution.

Karst Zone	Field Criteria				Factors influencing process differentiation		
	Topography	**Surface hydrology**	**Surface Landforms**	**Surficial cover**	**Predominant drainage system**	**Surface gradient**	**Other**
Kairuru	Dissected topography, plateaus and valleys	Stream sinks and risings common, sinks now disappearing close to contact	Karst valleys, solutional dolines, rillenkarren on ridges	Varying soil type, half - exposed	Allogenic - mixed	Steep	
Takaka Plateau	Undulating plateau, polygonal karst	No surface waterways	Solution dolines, uvalas	Predominantly exposed, varying soil types	Autogenic	Low	
Canaan South	Rolling downlands, enclosed basin	Intermittently active fluvial systems, centripetal stream sinks system	Polje, fluvio-karst valleys, alluvial dolines, limited karren	Extensive non - calcareous sediment cover, aggradation terraces	Allogenic	Low	Enclosed basin
Canaan North	Rolling hills and valleys, linear valley to escarpment edge	Stream sink close to karst contact, intermittently active waterways	Karst valleys, solution and alluvial dolines	Mostly non – calcareous sediments, quartzite	Allogenic	Low - moderate	
Pikikiruna	Rolling hills and valleys	Intermittent and active fluvial waterways, large stream sink	Alluvial dolines, karst valleys	Mostly non – calcareous sediments	Allogenic	Low - Moderate	
Takaka Walkway	Undulating plateau	No surface waterways, sink close to contact	Collapse dolines, grikes,	Thin; mostly rendzic soils and intergrades	Autogenic	Low	Development dominated by high secondary permeability
East Takaka	Highly dissected topography, plateaus, valleys and gorges	Intermittently active waterways,	Karst valleys and gorges, scree slopes, collapse dolines	Varying soil types, half exposed	Allogenic - mixed	Very steep	
Pohara	Moderately dissected topography, knolls, cliffs and terraces	Intermittently active waterways, stream sinks	Grikes, kamenitzas (solution pans), solution dolines	Tertiary sediment cover, exposed ridges	Allogenic - mixed	Moderate	Coastal processes influential in karst landform development

Table 6.1. Summary table showing comparisons between attributes in the karst zones and the predominant influences on landform development. See text for explanation,

It is important to note that this table simplifies the relations between the observed geomorphology and the factors that assist in differentiating erosional processes. The more complex relations between the hydrological systems and surface gradients, which interact to form a complex history of landform development, are discussed below.

6.3.1 Denudational System

The recognition of the predominant recharge style is of particular significance to understanding karst evolution. The type of recharge (Figure 6.3) is of particular significance to the water chemistry. Solution by allogenic waters is produced by high volume, calcium-undersaturated flows. Allogenic waters, because they are associated with enlarged conduits, can penetrate the subsurface more rapidly and to a greater depth and thus, have the ability to corrode more intensely below the surface (Dowling 1974, Williams 1968). This explains why caves are more common in association with allogenic inputs.

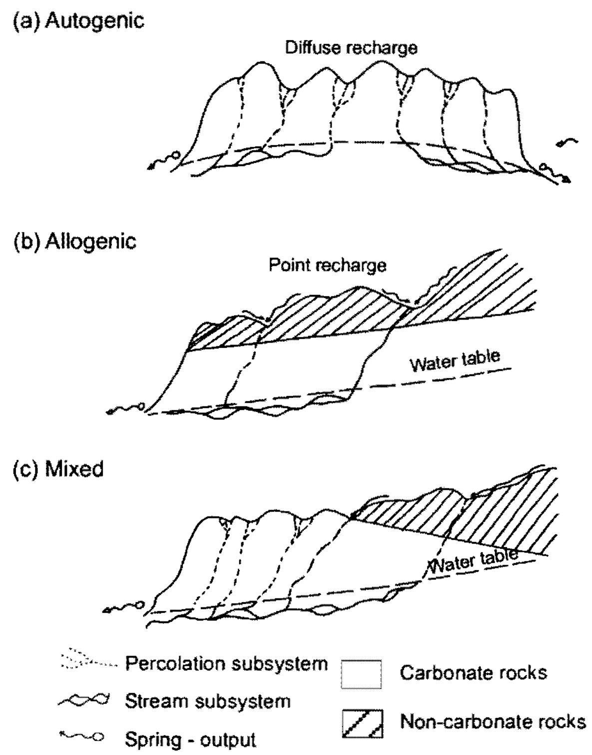


Figure 6.3. Karst denudation systems. The intermediate case (c) is the most common in the study area. (modified from Ford and Williams 1989)

Solution carried out by autogenic percolation involves slowly permeating waters that, because they become chemically saturated soon after contact with the carbonate rock, can only corrode the rock close to the surface. Although denudation by autogenic waters is diffuse and restricted to the near surface, the solution is more intense. Dowling (1974) notes that this is probably because the solution is enriched by CO_2 derived from the soil during infiltration and because the slower seepage rates ensures the solution has a longer time in contact with the rock surface.

Solution in an autogenic system therefore, being diffuse and generally uniform, results in the development of dolines and in surface lowering of the carbonate bedrock, whereas the concentrated and relatively large inputs from allogenic denudation operate to incise gorges and enlarge conduits and caves. The impact of concentrated versus diffuse drainage is reflected in the surface lowering of the marble surface. Where diffuse autogenic solution prevails (as on the plateaus) the entire surface is denuded by at least 400m, in contrast, the gorges in East Takaka indicate that focused corrosion has removed up to 1000m of rock but only in the line of the river. Figure 6.4 summarises the major influences and variations associated with the differing drainage systems (after Williams 2001, 1992, Ford and Williams 1989, Trudgill 1985).

Most karst systems fall in between the two extremes and denudation is accomplished by rain falling directly on the carbonate rock and runoff from non-karst catchments (Williams 2001).

The allogenic and autogenic components of a karst systems are normally distinguished by hydrological and geochemical assessment of waters at the output boundaries (Ford and Williams 1989, Williams and Dowling 1979). Because internal karst catchments are not delineated and the boundaries of the karst zones do not correspond to subsurface hydrological connections, surrogate evidence such as the distribution of landforms and soil cover was utilised in this study to evaluate the recharge systems. As an example, the prevalence of mixed denudation systems can be recognised by the presence of solution dolines and fluviokarst features in all of the karst zones. Solution doline development is attributable to vertical autogenic or epikarstic drainage occurring throughout the karst system. The occurrence of caves systems and karst valleys, often filled with non-calcareous sediments, even in presently autogenic catchments indicates that at some stage of karst evolution, denudation involved concentrated allogenic runoff.

Although mixed or intermediate recharge systems are extensive throughout the study area, the predominance of allogenic or autogenic recharge can be recognised from an assessment of the relative frequency of the karst landforms in each of the karst zones

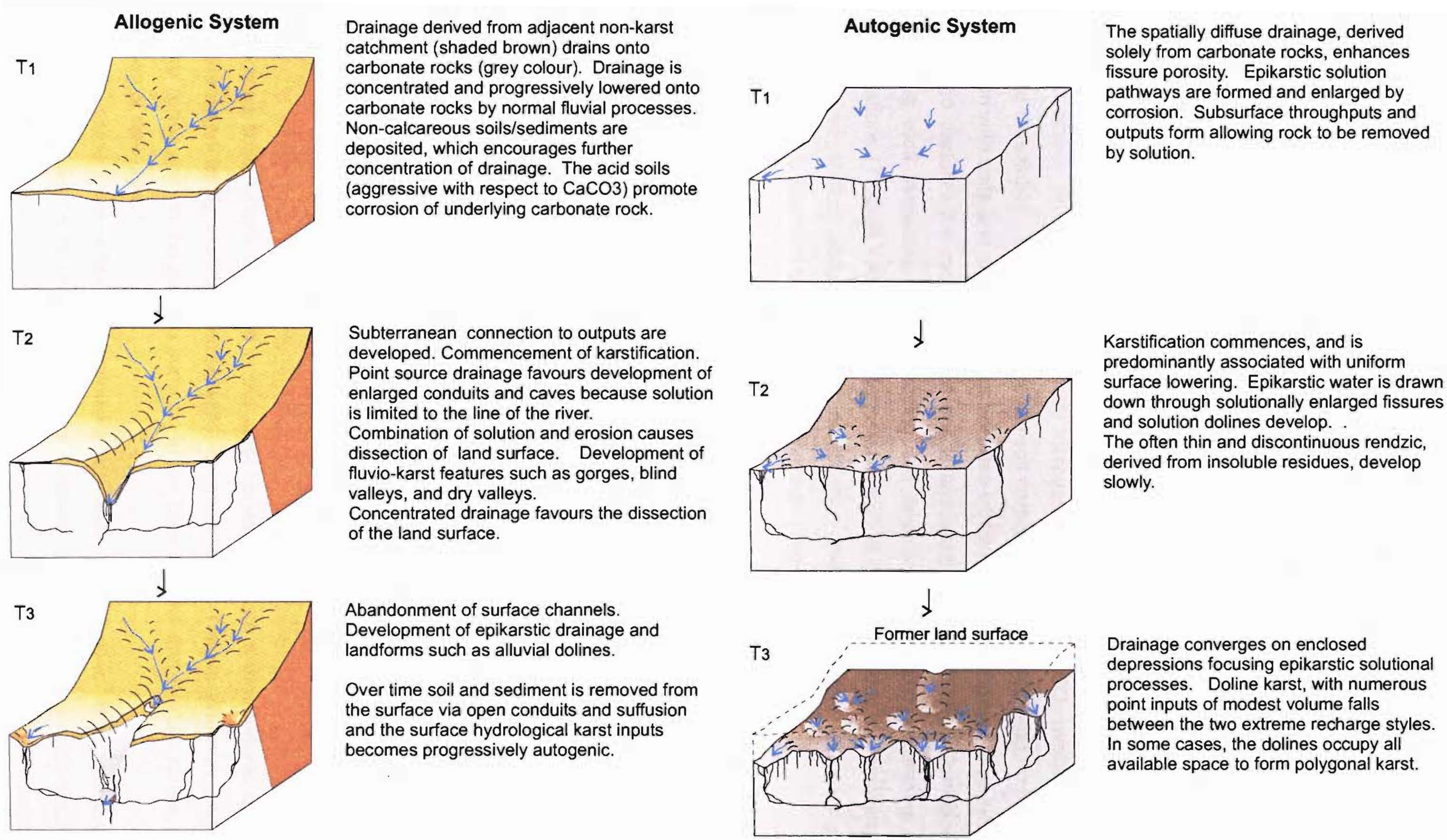


Figure 6.4 Idealised allogenic and autogenic denudational systems, showing the relation with soil and/or sediment cover and karst landform development over time (T). The recharge systems in the karst study area are mixed and vary greatly over space and time.

6.3.2 *Surficial Cover*

The distribution of differing soil types on the karst rocks is useful in ascribing a predominant denudation system to the karst zones and in understanding process variation. The nature or absence of soil (Map 1), sediment or vegetative cover influences the nature of the chemical reaction and the distribution of precipitation.

Outcrops and calcareous soil covered surfaces are the least affected by corrosion. Bare rock surfaces are only corroded episodically when rain, which is less aggressive than acid soaked solutions, falls directly on the rock surface (Trudgill 1985). The presence of non-calcareous soils and/or vegetative cover and the associated living organisms promotes solutional activity as these factors greatly increase the amount of CO_2 available for use in carbonate dissolution. Corrosion of the subsoil carbonate rock is enhanced, not only by the interaction with soils and organisms, but because of the increased length of time available for solution to dissolve the rock when the soil is saturated (Trudgill 1985). Corrosion of the underlying rock increases with increasing soil organic content and decreasing calcium concentrations (Trudgill 1985). Soil aggressiveness is greatest under low calcium content soils with vegetation adapted to acid conditions, whereas chemical weathering of the carbonate rock is subdued by calcium rich rendzinas (Figure 6.5).

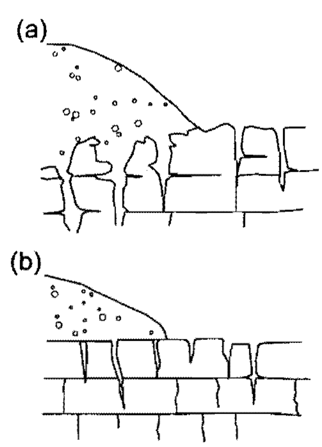


Figure 6.5. Soil type and subsoil erosion of limestone. (a) acidic non-calcareous soils and eroded limestone. (b) calcareous soils and protected limestone. (adapted from Trudgill 1985)

Calcareous soils, where observed in the karst zones, correlate with autogenic denudation. The characteristically skeletal rendzic soils, common in the Takaka Walkway and Takaka Plateau zones and on the plateau surfaces in the East Takaka and Kairuru zones, promote diffusion of drainage.

Although some non-carbonate sediments or soils are derived from autochthonous interbedded detrital rocks (as in the Takaka Walkway zone), most non-calcareous or acid soils and sediments are sourced from neighbouring non-karst catchments and deposited on the carbonate terrain by fluvial and alluvial processes. The Canaan South and Pikikiruna zones provide good examples of zones with an allochthonous supply of non-carbonate material. Sediment cover in these areas is often substantial especially when compared to the often thin and patchy rendzic soils.

Thicker deposits of sediment or soil may also focus drainage into areas of low relief and augment erosion of the karst, but seemingly only up to a point. Very thick deposits inhibit karst formation (Sweeting 1973), largely because very thick soils are buffered against changes in acidity (McLaren and Cameron 1996). Diminishing alluvial doline development at Canaan South appears coincident with the highest and apparently thickest terrace sequences (Map 2b).

The nature of the solution, whether under exposed or covered conditions, is particularly influential on karren morphology. Factors affecting karren development such as the lithology of the rock, the slope or dip of carbonate rock and associated structures (Chapter 3) are also important (Sweeting 1973). Nevertheless, the presence of cover and karren type are intrinsically related, Bogli (1980) uses surficial cover to differentiate free karren from half-free or covered karren. The distribution of karren in the study area is often indicative of the absence or presence of soil or vegetative cover in the zones. In particular, the lack of exposed (free karren) forms such as rillenkarren corresponds to those zones, such as Canaan South, Pikikiruna, and Canaan North where the drainage is largely allogenic and soil or sediment cover is extensive (Figure 6.6).

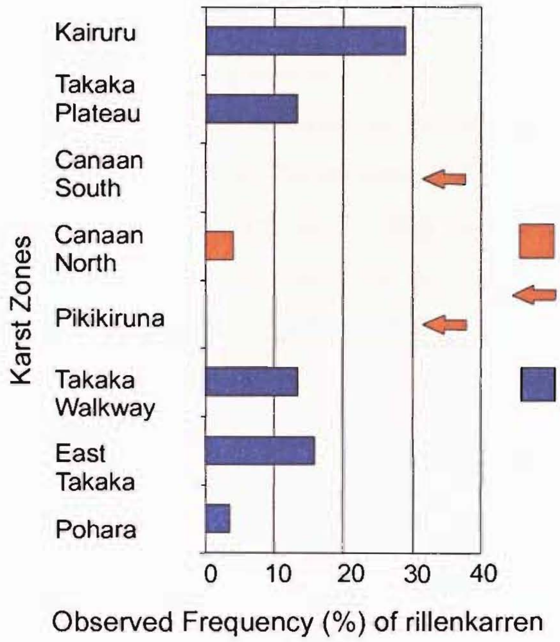


Figure 6.6. The difference in landform type and distribution and the association with surficial cover is particularly evident from the prevalence or absence of rillenkarren, the distribution of which are very limited in zones with extensive deposits of alluvial cover.

6.3.3 Surface slope gradient

Perhaps more applicable to the study area than other areas, because of the changes in relief caused by uplift, differences in slope gradient are fundamental to understanding the differences in the karst zones (Figure 6.7). Because of the lowered base level and high hydraulic heads, the potential for vertical solution throughout the study area is high, yet surface gradients appear to determine the proportion of vertical or lateral solution. Overland flow dominates on steep slopes. Vertical solution is more prevalent on low angle surfaces.

Doline development appears closely related to surface gradient. A review of the geomorphological maps (Maps 2a - e) reveals that doline development is largely constrained to slopes less than 15°. Doline karst and doline fields are better developed on horizontal or sub-horizontal surfaces. Dolines become increasingly elongated in the direction of drainage with increasing slope. Once surface runoff or lateral solution exceeds (at an undefined threshold) vertical solution, the epikarstic drainage appears restricted and dolines fail to form. Thus, the largest number of dolines occurs in those areas with well-developed vertical solution pathways, such as the Takaka Plateau and Canaan North. Based on doline numbers, vertical drainage is less developed in the East Takaka, Kairuru and Pohara karst zones.

The impact of slope gradient and overland flow is particularly important in the allogenic zones. Where slope gradients are low, the area is initially dominated by lateral planation and progressively by vertical solution. The allochthonous sediment influx results in the aggradation of alluvium and sediments and/or soils. The effect of aggradation under low slope conditions is reflected in the presence of alluvial dolines (Figure 6.8), which are formed by vertical denudation of the underlying carbonate rock and mechanical suffusion of overlying sediments. Steeper gradients and overland flow, however appear to facilitate the transportation of allochthonous sediments.

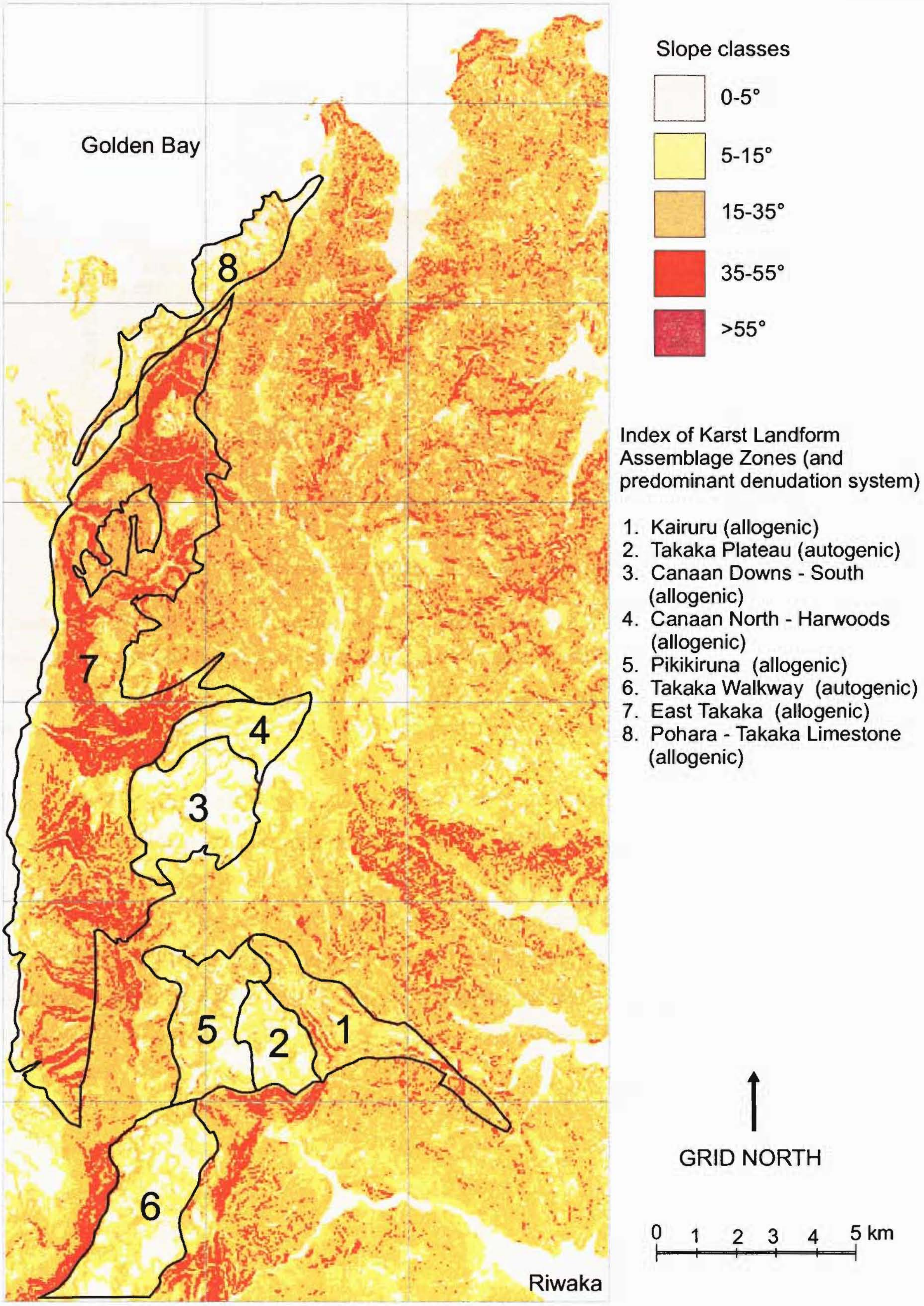


Figure 6.7. Slope gradients and karst landform zones. The influence of the slope gradient is particularly evident in the zones dominated by allogenic recharge. Overland flow, vertical incision and lateral solution are more prevalent in those zones with steeper gradients such as East Takaka and Kairuru. Zones with lower gradients are more likely to be dominated by vertical solution.

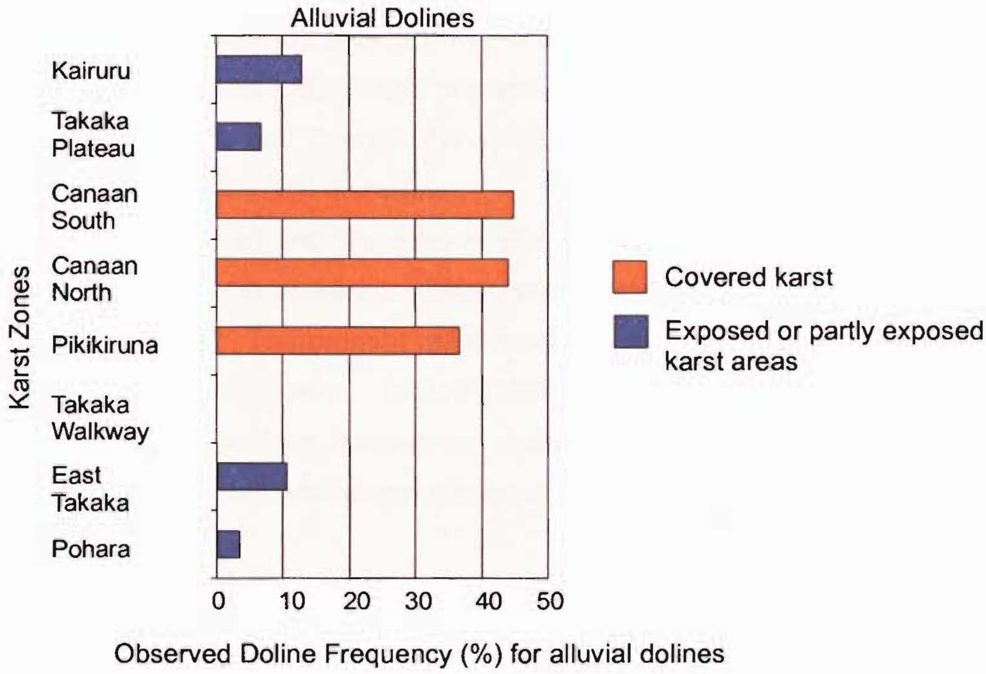


Figure 6.8. Alluvial doline development. In those zones with allogenic recharge and low slope gradient the surfaces become covered with allochthonous sediments, resulting in the prevalence of alluvial dolines. Although allogenic inputs are common in the East Takaka, Kairuru and Pohara zones, the steeper slopes and overland flows inhibit aggradation of sediments.

Those zones dominated by allogenic recharge and steeper slopes (Table 6.1) tend to have more lateral solution and vertical incision. Although the development of steep-sided gorges is largely controlled by relief which in turn is caused by tectonic uplift, the gorges also reflect the dominance of overland flow over vertical percolation (Williams 1993). Steep sided gorges (such as Gorge Creek and Dry River, East Takaka), persist in karst terrain because a dissolved load is easier to transport than a suspended or clastic load, and slope processes which result in slope decline (Figure 6.9) are not as dominant in karst terrains (Jennings 1971).

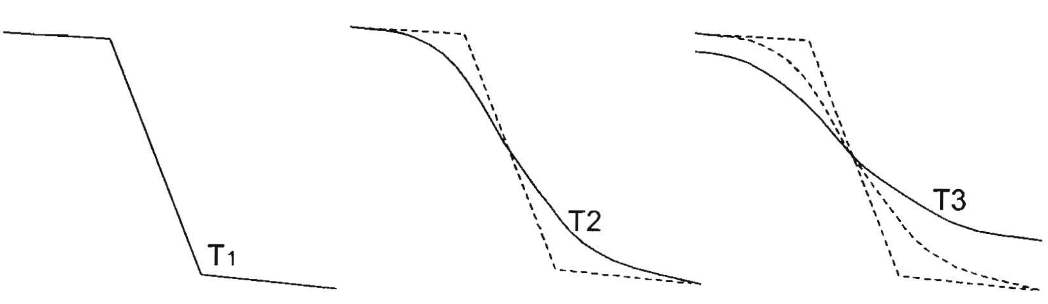


Figure 6.9. In contrast to karst terrain, slope processes (such as mass movements and slope wash) in non-karst landscapes cause erosion on upper slopes and deposition (or slower erosion) on lower slopes resulting in 'flattening out' of scarps over time (T).

Observations of the escarpment adjacent to the Takaka Walkway zone indicates that steep slope gradients in autogenic catchments are also maintained, most likely by the lateral flow of water over the surface and through the epikarst, but the absence of focused allogenic inputs results in a lack of surface dissection.

It is important to note that the dominance of overland flow is reduced over time, with increasing karstification and epikarstic development, lateral flow is progressively captured vertically (Williams 1993). The present relief and predominance of lateral flow may indicate the present stage of development. Trudgill (1985) observes that in the sequence of karst evolution, a high level surface incised by rivers represents the first stage, with relief becoming maximal at the half way stage of karst development.

6.4 Summary

Karst landform development, as with many natural systems, is interrelationary. The karst attributes observed and quantified in the karst zones are attributable to differentiation of the main landforming processes; solution and mechanical erosion. Variations in these processes is largely caused by interacting changes in soil cover, slope gradient and denudation type. On the basis of the most influential variables in landform evolution, the karst zones in the study area can be roughly divided into three main types:

1) *Predominantly autogenic.*

Surface landforms occur in response to both long term and active autogenic recharge. This group, which includes the Takaka Walkway and Takaka Plateau zones, is similar to the holokarst, or true karst, of Sweeting (1973) in that solution is the dominant process and all or much of the drainage is underground. The gently undulating topography in both zones reflects the uniform surface lowering accomplished by spatially diffuse drainage. These zones support well-developed epikarst. Rendzic soils and intergrades are common. The mostly exposed karst surfaces, hosting numerous and well-formed dolines, are widely recognised for their visual impact. The differences between the zones, namely the prevalence of grikes and collapse dolines in the Takaka Walkway and the dominance of large solution dolines and uvalas in the Takaka Plateau results from differences in the density of structural features and the related vertical permeability.

2) *Predominantly allogenic with low angles slopes.*

The predominant landforms in these zones, karst valleys, occur in response to the past and present dominance of combined fluvial and solutional processes, distinguished as fluviokarst by Sweeting (1973). The concentrated allogenic recharge favours the enlargement of conduits and development of cave systems. This group, which comprises the Canaan South, Canaan North and Pikikiruna zones, is characterised by low angle slopes and largely enclosed basins resulting in the aggradation of sediments and lateral planation of the karst valleys. The zones are characterised by the often extensive deposits of largely non-calcareous sediments, derived from the adjacent non-karst (granite and schist) catchments. The low gradients have also allowed for the development of vertical drainage through the overlying surficial cover resulting in the prevalence of many, small, alluvial dolines. The development of the epikarstic zone varies. The Canaan North zone, with a larger component of autogenic drainage, is the most well-developed of the three karst zones, with the Canaan South Zone considered as the least.

3) Mixed denudation systems with higher slope gradients.

Many of the larger landforms reflect fluvial processes and focused allogenic drainage. A fundamental feature of this group, which includes the East Takaka, Kairuru and Pohara karst zones, is the moderate to steep surface gradients and the resultant dissected topography. The surface drainage is becoming progressively autogenic as incision and headward retreat isolates allogenic inputs. The steep slope angles have resulted in overland flow, lateral solution and vertical incision. Vertical epikarst development is largely restricted to those areas of the zones with lower slope angles. The distribution of dolines is correspondingly, spatially restricted. The soil type and cover is highly variable reflecting the intermediate denudation systems.

In contrast to the East Takaka and Kairuru karst zones, lithological heterogeneity in the Pohara karst zone has resulted in the development of grikes and kamenitzas. Sea level changes and the action of coastal processes has produced coastal karst form and enhanced cliff development.

The complexity of karst landform evolution is summed up by Jennings (1971, pp221) who states that "the artificiality of separate discussion in this and previous chapters of the operations of individual factors differentiating karst has been made patent by inevitable cross references. Most karst evolution is complex, both on the surface and underground".

CHAPTER SEVEN – ENVIRONMENTAL IMPACTS

7.1 Introduction

This chapter examines the effects and impacts of human activities on the karsts.
Discussions in this chapter focus on;

- Presenting the rationale used to distinguish natural changes from human induced changes.
- Assessing impacts on the karst terrain from human induced change, particularly soil erosion and sedimentation and to a lesser extent, water quality.
- Evaluating the vulnerability of the karst zones to human induced changes.

7.2 Assessing geomorphological change

A comparison of the different processes and evolution in each of the karst zones indicates that differences, such as slope gradient and denudation type, that appear rather minor at the scale of the whole karst terrain can result in divergent landform development. It follows that just as natural changes to the karst system modify the response of the developing landforms and drainage systems, that human induced changes also impact on the karst and influence evolution.

An understanding of landform evolution in the karst zones can be used to recognise and distinguish the impacts of natural changes from human induced change. Many of the natural changes in the study area, including uplift, erosion, sea level oscillations and climate changes occur over scales of many thousands of years, adjustment to these changes is correspondingly gradual (Figure 7.1). Some changes, induced naturally, are sudden. Earthquakes for example, are known to alter hydrological connections instantly while mass movements may result in a deluge of sediment to a surface or subsurface stream.

Human induced changes and impacts are noticeable throughout the study area. People first settled on the karsts of the Riwaka and Takaka area around 100 years ago and the time available for human induced change to the karst has been relatively brief. Thus, the rate of anthropogenic change is very rapid (Figure 7.1). Many of the human activities not only affect rates of change but also constitute a change in process.

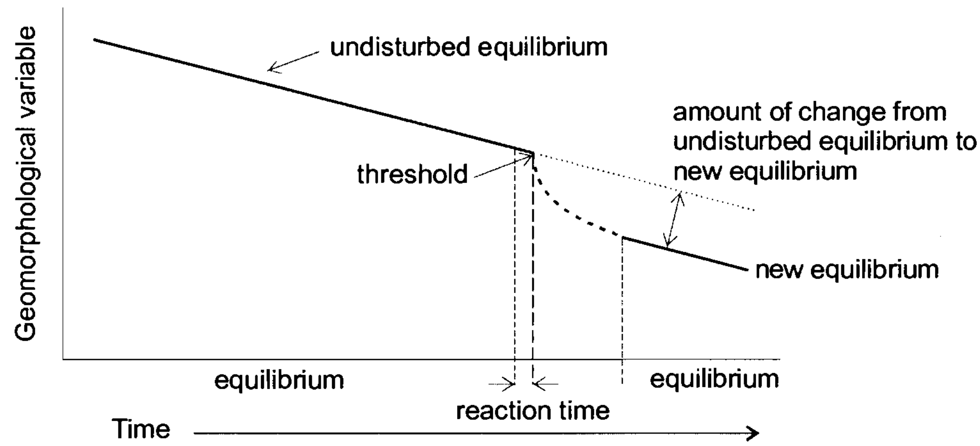


Figure 7.1. Theoretical response of karst system to relatively rapid natural or human-induced change (adapted from Cooke and Doornkamp 1990). The karst is continuously evolving (undisturbed dynamic equilibrium) as natural processes (chemical and mechanical denudation) are constantly operating. Induced change such as tectonic uplift or deforestation cause a shift in the equilibrium of the karst system. The karst eventually adjusts to the new conditions.

The response of the karst to change is complex. The karst zones, in which natural processes vary, may respond differently to the same human induced changes. The complexities of determining environmental change are outlined by Cooke and Doornkamp (1990). Difficulties in investigating change arise because factors such as the thresholds required for the system to change, the reaction times between activity and impact, and the amount of change are hard to quantify.

7.3 Main impacts on karst

The karst in the study area is most commonly used for agriculture, residential development, tourism, forestry, and quarrying. Many activities carried out by people are not intended to impact on the karst or surrounding environments (Figure 7.2). Williams (1993) and Goldie (1993) recognise the difference between direct effects and indirect consequences of those effects, for example between the deliberate deforestation of an area and the unintentional effects of soil erosion and sedimentation. Williams (1993, pp 8) notes that "many impacts are indirect, but not necessarily any less damaging because of that".

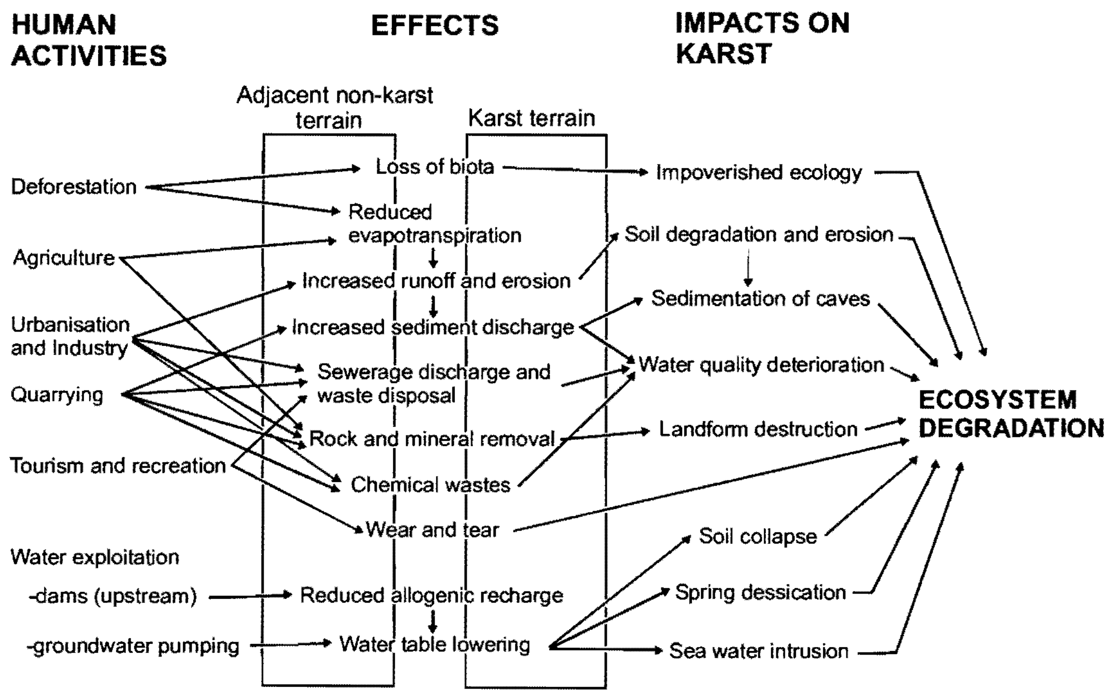


Figure 7.2. Human activities, their effects and impacts on karst terrains. Activities on adjacent, upstream non-karst areas often impact on karst as a result of runoff draining into karst. (Williams 1993)

Evidence from this study indicates the most widespread impacts occurring in the karst, as a result of human activities are changes to soils, sediments inputs and water quality. Because land clearance is the most widespread activity in the study area, this study focuses on the effects and impacts of soil erosion and the potential for sedimentation.

This section presents the evidence for soil erosion and inferences made regarding sedimentation and water quality. Less spatially extensive impacts such as landform modification and ground collapse are discussed in the following section. Examinations of soil erosion included soil depth sampling and assessments of changes to landforms. Karren, in particular, were used to assess changes to the soil and sediment cover, the time in which karren develop corresponds to the time available for human impact.

Confidence in evaluations of sedimentation and water quality are limited by the reliance on qualitative assessments. Although the impacts are widely observed, the difficulty of obtaining quantitative assessment arises because of a lack of detailed hydrological knowledge regarding the subsurface drainage and the absence of long term and/or systematic monitoring of the karst systems.

7.3.1 Soil erosion

Soil erosion, induced by deforestation is as Williams (1993, pp9) states, "undoubtedly the most profound indirect impact of human activity on karst terrains". Land clearance was and is carried out for numerous purposes: to clear land for agriculture or residential housing, construction of roads, and for economic harvesting of native or renewable timber. The beginning of last century saw the most widespread removal of native forest in the study area, with clearance of smaller beech stands continuing under government supported schemes until the late 1970's (Millar 2002). Around 55% of the study area is presently covered by either native forest, regenerating scrub or to a lesser degree, plantation forestry. Of the remaining forests, 30% occurs in protected areas such as the Abel Tasman National Park. Privately owned, undisturbed forest areas occur in largely, inaccessible steep-sided gorges and escarpments. The more favoured sites for development, such as those areas with low angle slopes and extensive soil cover, are free of forest or scrub cover. Marginal farmland areas have been utilised for pine tree farming, but it appears that, increasingly, very steep and/or south-facing slopes are left idle.

Karst zones such as Takaka Plateau and Takaka Walkway, which are noted for their exposed and exposed and sculpted rock surfaces, reflect forest clearance and subsequent soil erosion as much as natural processes (Hardwick and Gunn 1993). The exposed bedrock terrains, where it now seems futile to have developed for farmland, provide evidence of the relatively rapid removal of vegetation and soils.

Accelerated soil erosion in response to human-induced change is noted in areas like the Burren, Ireland, where the present-day occurrence of large bare expanses of karst pavement are attributed to soil losses following deforestation and overgrazing (Goldie 1993, Drew 1983). Studies of soil erosion on karst in China have shown that, on newly cultivated slopes greater than 25°, entire soil profiles can be removed in under two decades (Lin et al. 1992, cited in Williams 1993).

It is important to distinguish between accelerated erosion and natural erosion (Figure 7.3). That natural erosion of unconsolidated soils and sediments and vegetative debris in the Takaka and Riwaka karsts has occurred is evidenced by the removal of sediments and soils throughout the Pliocene and Quaternary periods (Chapter six). Although background soil erosion rates in the study area have not been quantified, on-going soil transportation is likely to be enhanced by steeper slopes (McLaren and Cameron 1996) and the changes in base level.

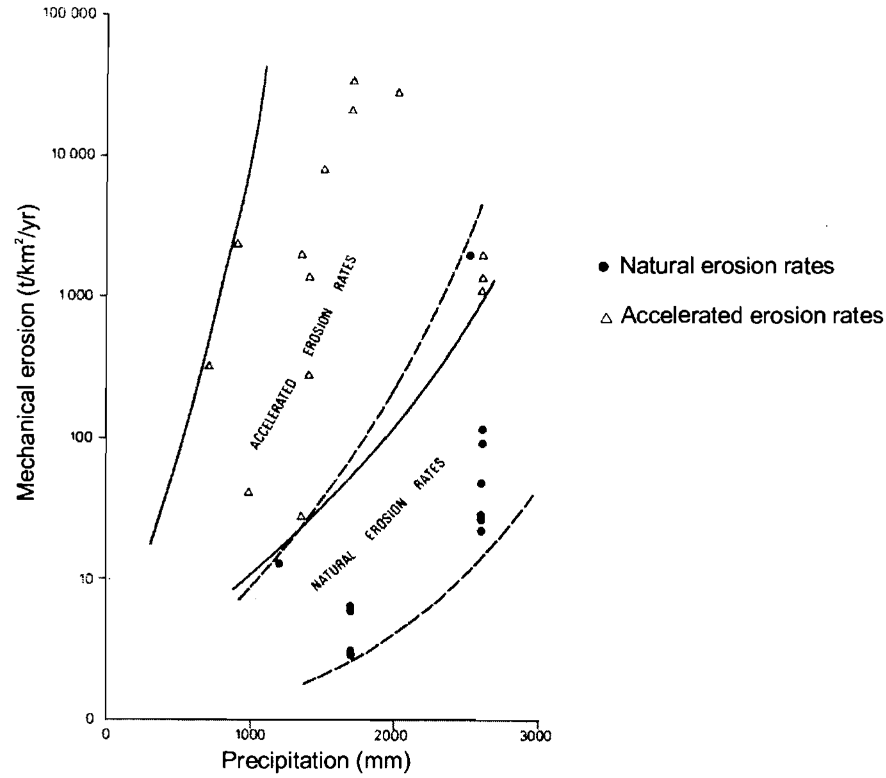


Figure 7.3. A comparison of the range of natural and accelerated soil erosion rates for a given mean annual precipitation in New Zealand catchments of various size, slope, and land use. Natural erosions rates are assumed to occur under relatively undisturbed natural vegetation (Williams 1980). Mean annual precipitation for the study area ranges from 1300 to 4500 mm.

Deforestation and soil disturbance greatly increase the likelihood of soil erosion (McLaren and Cameron 1996). Relatively high evapotranspiration rates in forested areas are converted to increased runoff when forests are modified to pasture. The subsequent modification of stream channels, greater frequency of flooding and a higher water yield result in increased rates of erosion. Water yields in a catchment may increase by up to 100% following land clearance, but often decline within the following 4-7 years if the area is revegetated (Fahey and Rowe 1992). Rainstorms, which are more erosive when raindrops impact directly on the soil, are an important agent of soil erosion. Granitic soils, comprising a large component of the non-calcareous soil cover are particularly prone to erosion. Fahey and Coker (1989, cited in Coker and Fahey 1994) in a study of erosion in the Separation Point Granites, noted that rainfall intensities of around 6mm/hr were required to mobilise the granitic soils (24 out of 132 rainfall events exceeded this threshold).

7.3.1.1 Assessment of Soil erosion

Accelerated soil erosion in the study area is evidenced by observations of soil losses occurring in relation to tree trunks and karren. Soil depth sampling was utilised to provide quantitative results of the soil losses in cleared and uncleared areas. Visible evidence of soil erosion is very common in the modified areas of all karst zones. Observations of vegetative cover or deforestation, karren and cut standing tree trunks were noted as part of the geomorphological classification sampling, with around 30 sampling sites occurring in each zone (Appendix A).

Cut standing tree trunks located throughout the study area provide graphic evidence of soil loss (Figure 7.4). The axe-marked tree trunks (commonly ~0.5m diameter) indicate that at least 10-30cm of soil cover has been lost since land clearance by settlers c.100 years ago. The trees appear to be very shallow rooting, a review of undisturbed forest areas reveals that a large part of the root system is maintained in organic soils and humus. The early technique of 'burning off" hand-felled forest debris would have resulted in an initial loss of organic forest litter and humic material. The disturbed soil and sediment cover, with surfaces directly exposed to rainstorms, would then be at risk of removal. Charred wood on the trunks and a lack of burn marks on the tree roots (Figure 7.4) indicates that much of the soil erosion occurred after clearance. A further obvious anthropogenic indicator of soil erosion is fences with posts suspended above a bare rock surface (Palmer, J. *pers. comm.* 2002).
Occasional markings on the sides of outcropping karren, which can be used to estimate the amount of induced soil erosion (Gams et al. 1993), also indicate that at least 10-20 cm of soil has been lost since modification of the cover (Figure 7.5).

That rundkarren is the most common solutional form observed (occurring at 58% of all sites visited) throughout the study area indicates significant changes have occurred to forest and soil cover in the recent past. The distribution of karren types in the karst landform assemblage zones can be used to infer changes in vegetation and/or soil cover. Sharpened small-scale solutional features, such as rillen- and rinnenkarren, are more common in the Takaka Plateau and Takaka Walkway zones and on the ridges of the Kairuru and East Takaka zones (Figure 6.6), where soils and vegetation are naturally sparse. In contrast, solutional processes are more evenly distributed under soil cover and the subsequent landforms are more rounded, rundkarren for example, forms only under covered conditions. Once exposed to aerial processes, the rounded solutional runnels are progressively altered to sharper rills, the modification of karren forms commonly occurring within tens of years. It follows that the dominance of exposed rundkarren throughout the study area also indicates that the karst system is still adjusting to anthropogenic changes (Figure 7.1).

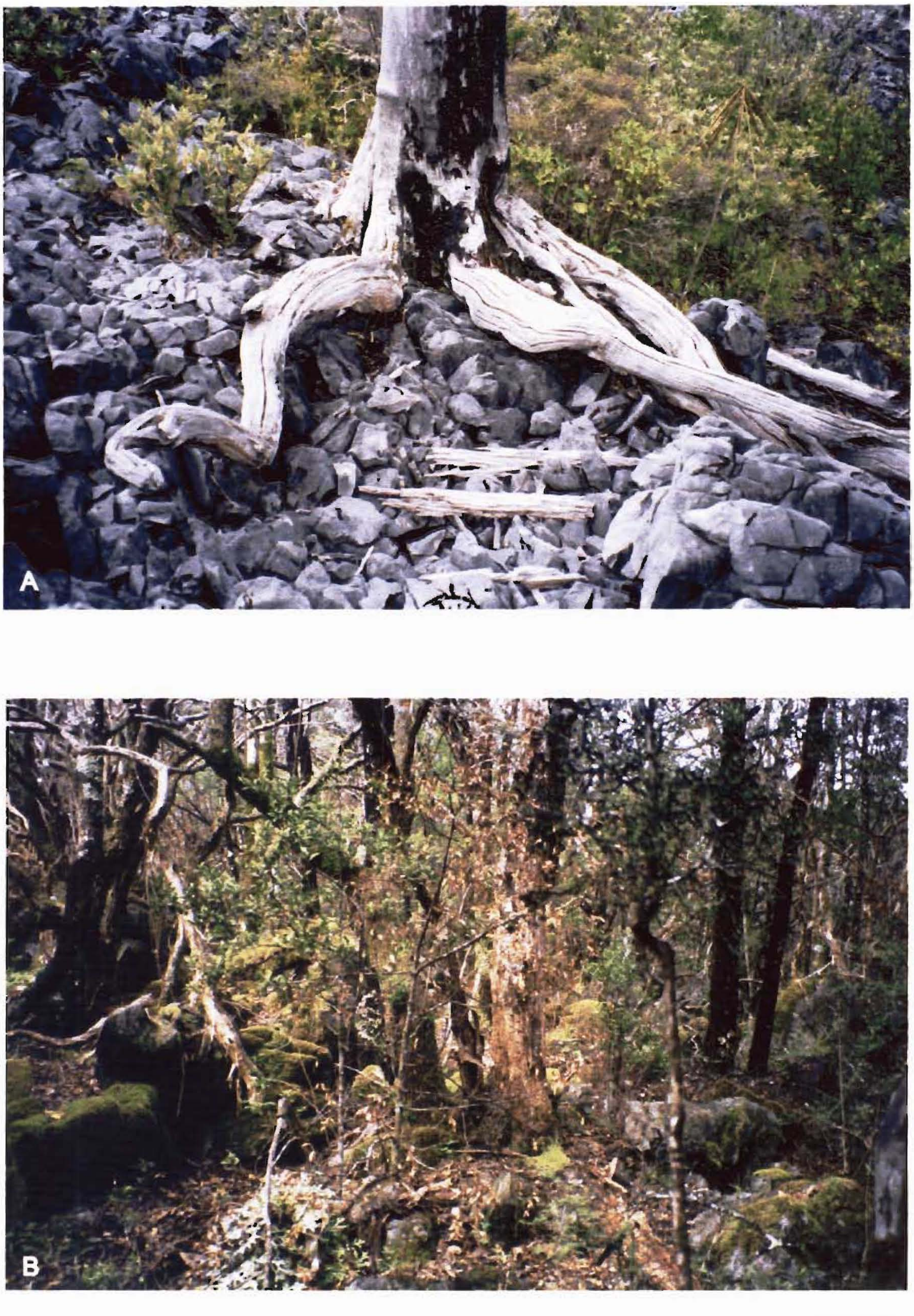


Figure 7.4. (a) Cut standing tree trunk (Takaka Walkway). The exposed roots give an indication of the amount of soil loss occurring after land clearance. Regenerating natives are observed growing in grikes, where the soil has now collected.
(b) Stunted forest with outcropping karren covered in moss and forest litter (Takaka Walkway). The forest canopy is only 5m high compared to forest growth on thicker soils where trees are commonly taller than 20m .

Figure 7.5. Induced soil erosion and exposure of rundkarren (Canaan South) as a result of soil losses after deforestation. The trees trunks have been cut. (a) At least 10cm of red-brown calcareous soil has been eroded as indicated by the remaining soil protected by the tree root. (b) Removal of topsoil and exposure of sub-aerially formed rundkarren. (c) Around 30cm of soil has been lost around the base of this rundkarren pinnacle, which probably outcropped under forest cover. Soil has been preferentially eroded on the right hand side which is commonly used by sheep (yellow rubbing marks).

Very occasional outcrops of karren occur under forest canopy, but the rocks are usually covered by organic debris or moss and not directly exposed to aerial conditions. The absence of karren under forest canopy is conspicuous when compared to the observed frequency of outcropping karren in modified areas. Extensive outcrops of karren in forested karst areas are restricted to the stunted forests, such as those found in the Takaka Walkway and on the ridges along the Harwood's Hole Track, where the native growth is impeded because of naturally skeletal soils (Figure 7.5). While vegetative cover inhibits aerial processes, rundkarren developed under thin forest canopy and acid vegetation (moss, lichen and humus) are distinct from rundkarren formed under extensive soil cover and subsequently exposed by soil erosion or road cuts in that the subsoil-formed rundkarren appear more rounded.

Evidence obtained from soil depth sampling in the Takaka Walkway area, shows that accelerated soil erosion has occurred in response to land clearance (Figure 7.6). Site descriptions are in Chapter three and sample site locations are shown on Map 2c. The greatest difference in mean soil depths was noted at site one where the sampling occurred along a ridge line. Occasional, largely individual, moss and forest debris covered marble pinnacles occurred under canopy in the control area, but where cleared, bare rock surfaces comprised around 30% of the surface area.

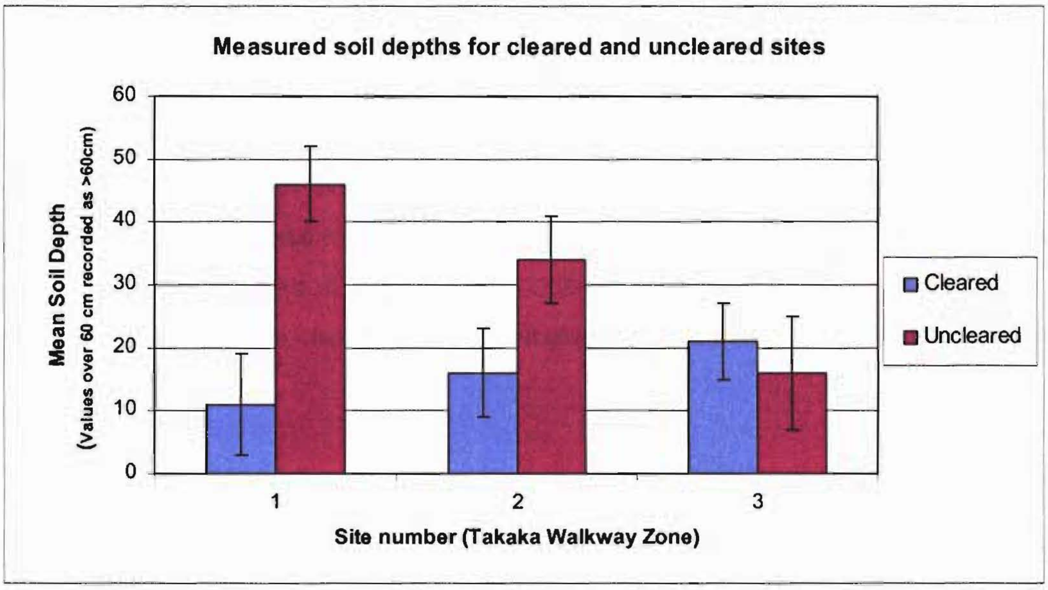


Figure 7.6. Effect of forest clearance on soil erosion. Site one occurs on a ridge, site two on a valley side and site three in the depression of a large shallow basin. The mean depths (total of 180 samples) of soil and organic material in the undisturbed control areas were greater than those in the cleared areas of the sites, with the exception of site three, where it appears the stunted native forest was preferentially left due to the scarcity of the natural soil cover.

In all disturbed areas the humus material, averaging around 7 cm in depth, was absent (see Appendix D). The difference between soil loss and remaining soil cover in the disturbed and undisturbed zones was not significant at site three. The undisturbed control site three comprised a outcropping bedrock surface beneath a stunted native forest. Soil cover is almost non-existent, and it appears that forest clearance was restricted to where the soil cover was considered sufficient to maintain pasture.

7.3.1.2 Inferences made from soil assessments

Variables which appear to enhance the rapid removal of soils and sediments are (a) the prevalence of naturally thin soils, (b) a high density of structural features and (c) steep slopes. Zones characterised by one or more of these variables are the most vulnerable to both natural and accelerated soil erosion. The ranking of zones from most exposed to most covered (Chapter four) reflects the susceptibility of some zones to soil erosion.

The induced removal of soil in areas such as the Takaka Walkway Zone and Takaka Plateau is likely to reflect the naturally thin nature of rendzic soils (more commonly found in these two zones), and the removal or relocation of soil into grikes and depressions in the epikarst zone. Shrubs and trees are commonly found growing in between grikes, where the eroded soils concentrate. Soils in the Takaka Walkway and Takaka Plateau zones are predominantly autochthonous, the rendzic soils developed from the residues remaining after rock dissolution. The purity of the marble in the study area enhances the natural sparseness of rendzic soils as only 1-2% of the original rock mass is available as a soil forming material. That visible rundkarren are more common in the Takaka Walkway and Takaka Plateau zones, relative to the other zones (Figure 5.2), indicates that it is these zones in which the vegetative or soil cover was most affected. The predominantly vertical relocation of rendzic soils in areas with increased permeability occurs after land disturbance despite the well developed structure of the soils, which promotes resistance to erosion (New Zealand Soil Bureau 1968).

Slope gradient is important in understanding soil erosion. The velocity of the surface water and subsequently, its erosivity is significantly increased with increasing slope angle. Sidle et al. (1985) note that soil mass movements are common on slopes over 35° (see Map 1). Therefore, the zones characterised by steeper slopes, Kairuru, Pohara, and especially East Takaka, are more at risk from soil erosion. That overland flow in steeper areas enhances transportation and loss of soils, is reflected in the scarcity of soils and sediments on most of the deforested ridges and steeper slopes throughout the study area.

The persistence of rendzic soils on some very steep slopes indicates that the variables controlling calcareous soil erosion are not fully understood. Tree-fall mounds likely to be associated with original deforestation and occurring on the steep slopes of the Pikikiruna Fault Escarpment (East Takaka) appear largely undisturbed (Figure 7.7).

Figure 7.7. Tree fall mounds are scattered over the steep sides of the Pikikiruna escarpment (East Takaka). The presence of calcareous soils on these steep slopes indicates the controls of rendzic soil erosion are not fully understood.

The potential for regrowth of the formerly extensive forests has been significantly reduced in some areas. The relative size of the tree (diameter) is used to give an indication of the thickness of the original (or undisturbed) soil cover; stunted forests correspond to very skeletal soils, while larger trees indicate that the soil cover is extensive enough to support significant forest growth. Large tree trunks now scattered over bare rock surfaces and the spatially restricted regrowth of shrubs and small trees in grikes gives testimony to the loss of soil productivity (Figure 7.4).

The loss of soil productivity in areas with extensive soil deposits remaining, is still of concern as it is often the most fertile topsoils that are removed (McLaren and Cameron 1996). While induced soil erosion has occurred in areas such as Canaan South, Canaan North and Pikikiruna zones, the remaining allogenic soil cover lessens the most visible effects of accelerated soil erosion (bare rock surfaces). Although often thicker, the soils remain susceptible to being washed down open fissures and cavities (Williams 1993) as evidenced by the formation of alluvial dolines and the presence of non-calcareous sediments in caves (for example, Starlight Cave).

7.3.2 Sedimentation

Increased sedimentation resulting from accelerated soil erosion poses a serious risk to surface and subsurface waterways. Subsurface stream channels and caves are particularly prone to damage. Karst streams and resurgences often appear to run clearer or contain less suspended sediment relative to surface rivers and streams, for example, the notable difference in the Riwaka (karst) and Motueka (non-karst) rivers after rainfall. Most of the suspended sediment load transport occurs in high energy flows or floods. This occurs not because less sediment enters the cave under normal flow conditions but because relative to surface streams, sediments in cave streams settle out in the quieter reaches. Under flood conditions, however, the energy of the floodwaters are sufficient to remobilise unconsolidated cave sediments.

The main factor controlling sediment yield is precipitation (Hicks and Griffiths 1992). As with soil erosion, increased rainfall and more intensive rainstorm events have the potential to increase the rates of runoff and transport more sediment through the drainage systems. Precipitation rates for the upland areas of the study area are higher (2500 -3000 mm/yr) than those near the coast, the Pohara karst zone, which because of the lower altitude and protected geographical location receives around 1400 mm/yr. The orographically controlled northerly rainstorms, which are typically short and heavy are likely to increase sediment yields. It is unlikely though, that climate variation between the karst zones are sufficient to differentiate the susceptibility of the karst zones to sedimentation.

It is inferred here that the primary factors influencing the vulnerability of the karst zones to surface and subsurface sedimentation is (a) the availability of soil or sediment material, which is closely related to soil erosion and (b) the predominance of allogenic inputs. Areas prone to sedimentation are likely to include those areas with a large allogenic catchment and concentrated allogenic recharge (Map 1). The Separation Point granite terrain that comprises a large portion of the allogenic catchment area is associated with sedimentation problems, particularly as a result of mass failures following land disturbance (Coker and Fahey 1994). The drainage networks focus increased sediment yields and the sediments are directed into caves, which are more commonly associated with point source runoff.

Because the natural soil cover is relatively thin and collected by surface irregularities, and surface runoff is constrained by the prevalence of vertical drainage, autogenic areas are considered least susceptible to problems associated with sedimentation.

Millar (1997) noted that terrestrial troglobites often live in cave passages with streams prone to a degree of inundation. The animals rely on the input of detritus and other foods supplied by sediments and thus, cave fauna are susceptible to being smothered by increased sedimentation.

The problem of sedimentation in caves is highlighted by studies of the Waitomo Cave and catchment. It was recognised that in addition to destroying aquatic cave fauna (including glowworms), sedimentation may abrade delicate cave formations, impede the flow of water and/or completely block the supply of water and energy to the cave (Waitomo Catchment Trust Board 2001). Photos of the cave over time were used to confirm the increased obstruction of the cave entrance because of sedimentation. In 1889 the passage height of the cave entrance was 6m, in 1962 the height of the entrance was 3.7m, and in 1972 the submergence was only 2.7m high. Williams (cited in Waitomo Catchment Board 2001) used sediment cores to confirm accelerated aggradation in the catchment:

Historic (10 000 yr) aggradation rate	0.3-0.5 mm/yr
Average 20th century aggradation rate	30-40 mm/yr
Peak aggradation rate (during major road upgrades in the 1970's)	60 mm/yr

The connectivity of cave streams in the study area to anthropogenically induced sediment inputs is reflected in caves such as the Riwaka Resurgence, where sawdust is found in the Riwaka Resurgence Cave stream. Discovery of the Perseverance Cave occurred soon after beech tree harvesting in the late 1970's, and new deposits of silt and beech leaves up to 8m high were noted in some cave passages (Millar 2002). The cave has not been re-entered to determine if further sedimentation occurred.

7.3.3 Water quality

That much of the local water resources are derived from karst aquifers increases the importance of preserving the quality of and/or preventing contamination of karst waters. Ford and Williams (1989, pp 518) observe that because of the dominance of rapid fissure or conduit flow "karst aquifers are notoriously effective in transmitting rather than treating pollutants". Because soils, which provide a significant means of purification (McLaren and Cameron 1996) are scarce, the capacity of the karst to filter or decompose solid wastes and pollutants is further reduced.

Many of the upland areas comprise catchments for springs resurging at base level. Water, and any contaminants, travel through the karst system very rapidly, for example, waters sinking on top of the Takaka Hill at Summit rise at the Riwaka Resurgence within 24 hours (Table 2.1). The susceptibility of subsurface streams to contamination is observed in the resurgent water of springs such as the Riwaka Resurgence and Gorge Creek. The quality of the spring waters, which have elevated nitrate (derived from animal wastes and/or fertilisers) and coliforms levels (used an indicators of the presence of bacterial pathogens), is similar to that found in surface streams affected by farming practices. While local residents use the water issuing from the Gorge Creek Spring without an adverse effect on health, local dairy farmers are unable to utilise the Gorge Creek resurgent waters in milksheds because coliform counts exceed the levels recommended by Dairy Farming Best Practice (Manson, B. *pers. comm.* 2003). The misconception that karst springs are pure is highlighted by the number of people observed filling water bottles at stream risings such as the Riwaka Resurgence.

A primary factor in understanding the vulnerability of karst aquifers to contamination is the recognition of the unique drainage networks circulating from the surface to the spring outlet (Smith 1993). The hydrology of a karst area can be separated into point source or non point source inputs as outlined in Table 7.1.

Hydrological inputs	**Recharge type**	**Throughputs**	**Average Velocity**	**General**
Point source	Includes all allogenic inputs and autogenic inputs from closed depressions	Turbulent flow via conduits	10 – 1000 m /hr	Rapid recharge of pollutants into system, minor filtering.
Non point source - diffuse	Includes diffuse autogenic recharge not focused by karst depressions	Laminar flow via tight fissures	<10 m /hr	Contaminants less rapidly dispersed. Difficulty in providing known linkages from surface pollution to groundwater sources.

Table 7.1. Summary of end member karst hydrological processes (compiled from Smith 1993). Non point inputs are restricted to the Takaka Walkway zone and to a lesser extent, spatially limited areas of the karst where fractured rocks outcrop.

Point source connectivity is established for a limited number of sinks (Dowling 1974, Williams and Dowling 1979) and non-point source connections have not been determined because of the difficulties associated with tracing diffuse inputs. Thus, discharge sites for groundwater and possible contaminants cannot be accurately predicted. An evaluation of water quality degradation is also constrained by the lack of information regarding underground drainage patterns. Discharge – related samples collected at very short time intervals are required to identify underground drainage patterns (Smith 1993). Local water quality monitoring carried out three-monthly is sufficient to detect contaminants but is inappropriate as a means to understand karst aquifer contamination.

Current and potential sources of contaminants include sediments, sewerage effluent, stormwater discharge, animal wastes, road side runoff, agri-chemicals and fertilisers, and chemicals applied for weed and pest control (Hardwick and Gunn 1993, White 1988). Because point source inputs and output connections are more easily identified, and throughflows are often direct and rapid, prevention or control of point source pollution is easier than for diffuse inputs (Smith 1993).

7.4 Land use based impacts and vulnerability of the karst zones

The correlation of cleared land to karst geological contacts indicates that settlers preferentially developed karst areas, probably because of the fertile calcareous soils. The geomorphology of the karst zones often relates to opportunities for land use. Karst zones dominated by autogenic drainage and rolling topography (Takaka Walkway and Takaka Plateau) are presently used for low intensity pastoral grazing with the lack of surface water, exposed bedrock surfaces and thin soils constraining further development. Zones characterised by low slope gradients and significant soil cover (Canaan South, Canaan North and Pikikiruna) are more intensely used, with improved pastures and some residential development. Because steeper slopes and partly exposed surfaces generally limit intensive use of the land, zones such as East Takaka, Kairuru, and Pohara maintain largely pasture, forest cover, forestry developments and a small number of residences. Proximity to the coast and accessibility of the lowland Pohara karst zone means that land use is more intense compared to the other two zones in this group. Residential development is increasing, and the population in the Pohara – Tarakohe area is growing, with land use becoming progressively urban.

There is, however, no correlation between the potential for land use and the vulnerability of the karst. Karst vulnerability is defined by the Forest Practices Branch (2002) as the susceptibility of a karst ecosystem to change. The criteria given by the Forest Practices Branch (2002) for 'very high vulnerability': well-developed epikarst, high density of surface karst features, known caves, high level connectivity between the surface and subsurface, and numerous single and coalescing surface karst landforms, indicates that almost all of the karst in the study area is highly susceptible to change. While the karst in the study area is recognised as highly vulnerable, this scheme, developed for forest harvesting in British Colombia, is not appropriate for assessing local karst environments and does not account for the impacts produced by different human activities or land use.

The vulnerability of the karst in the study area relates to the inherent characteristics of the karst zones as recognised in earlier chapters. This section evaluates the potential impacts and susceptibility of the different karst zones to changes caused directly or indirectly by people. An understanding of the effects of people on karst is important not only for assessing how these changes may impact on the karst systems, but for how the changes may affect the way people use the karst resources. The main objective of karst management is not only to safeguard the karst itself, but in the study area where the karst is widely used, it is imperative to protect the resources sustaining local people and local economies.

Assessments of the susceptibility of the karst zones to soil erosion, sedimentation and water quality degradation are summarised in Tables 7.2-7.4, and discussed in further detail in the following sections. This section also reviews some of the other impacts common to the karst with regard to associated land uses. It is important to recognise that the susceptibility or risk of impacts (*risk = probability x vulnerability*) is different in those areas which have already been modified compared to those areas of the zones that remain undisturbed (Tables 7.2-7.4). For example, undisturbed rendzic soils in the zones of the autogenic group (Takaka Walkway and Takaka Plateau) are highly vulnerable to soil erosion because of the natural scarcity of soils and the high potential for vertical relocation. In the cleared areas, however, the land has already been deforested and soils eroded resulting in large expanses of bare rock surfaces. The probability of further clearance and potential for soil loss is therefore reduced.

The following assessments of land use based impacts on the karst focuses on the physical effects of human activities. An attempt to evaluate the more social impact of environmental change is beyond the stated purpose of this research. It is interesting to note though, that landscape values alter according to the proposed land use or perception of the user. For example, the outcropping rock surfaces in the Takaka Walkway zone, representing human induced soil erosion and karst degradation are presently very marginal as farmland. The barren marble surfaces are however, now recognised and protected as a significant karst area and comprise a valued walkway destination.

Geomorphological group	Zones	Natural susceptibility to erosion*	Reasons	Vegetative cover	Present susceptibility to induced erosion**	Reasons
predominantly autogenic	Takaka Plateau	high	Naturally thin rendzic soils and intergrades	regenerating natives, marginal pasture	low to moderate	Low intensity grazing, soil loss already occurred in disturbed areas, large areas scrubland regenerating,
	Takaka Walkway	high	Naturally thin rendzic soils, high frequency of fractures	marginal pasture, undisturbed forest in south	low	Reserve area, soils already eroded where cleared, low intensity grazing
predominantly allogenic, low slope angles	Canaan South	low	Low slopes, non-calcareous sediments and soils	pasture and scrub	moderate	Improving pasture
	Canaan North	low	Low slopes, non-calcareous sediments and soils	pasture on karst, forested non-karst catchments,	moderate	Improving pasture
	Pikikiruna	moderate	Moderate slopes, mixed soils	regenerating natives, scrub on steeper slopes	moderate to low	Moderate slopes, retirement of farming or logging areas
mixed drainage, high slope gradients	Kairuru	moderate	Moderate - steep slopes, mixed soils	pasture, scrub on ridges and steeper slopes	moderate	Steep slopes, some regenerating scrub
	East Takaka	high	Steep slopes, moderate fracture frequency, mixed soil	pasture, scrub and forest on ridges and steeper slopes	moderate to high	Steep slopes, track clearance, building infrastructure and forestry harvesting
	Pohara	moderate	Moderate slope angles, non-calcareous soils and sediments	pasture, scrub and forest on ridges and steeper slopes, highly modified areas (housing)	moderate to high	Changing landuse, building, infrastructure and forestry harvesting

* Erosion of soils within the karst terrain.

** Qualitative assessment of risk based on present geomorphological conditions and landuse. If an area is undisturbed then potential for induced erosion can be taken as that for natural susceptibility

Table 7.2. Interpreted vulnerability of the karst zones to accelerated soil erosion as a result of human induced change.

Geomorphological group	Zones	Predominant hydrological input type*	Natural susceptibility to sedimentation	Reasons	Risk of sedimentation of streams and caves**	Reasons
predominantly autogenic	Takaka Plateau	autogenic point source, non-point source	low	Thin soils, catchment areas restricted to dolines	low	Soil cover already scarce, no large sediment inputs
	Takaka Walkway	Non-point source	low	Diffuse drainage	low	Soil cover already scarce, no large sediment inputs
predominantly allogenic, low slope angles	Canaan South	point source (allogenic)	high	Steeply rising sides of granite catchment, very focused allogenic input	high	Drainage very focused, surrounded by steep, partly cleared, non-karst catchment, extensive unconsolidated soil and sediment deposits
	Canaan North	point source, (allogenic and autogenic)	high	Large granite catchment, focused drainage	moderate	Non-karst catchment, largely in National Park, some land improvements, focused drainage
	Pikikiruna	point source (allogenic)	high	Steeply rising non-karst catchment, very focused drainage	moderate to high	Drainage very focused, surrounded by steep, partly cleared non-karst catchments, extensive soil and sediment deposits. Increasing scrub regeneration, some forestry
mixed drainage, high slope gradients	Kairuru	point source, (allogenic and autogenic)	moderate to high	Steeply rising non-karst catchment, focused inputs	moderate	Catchment areas regenerating, steep slopes, focused drainage
	East Takaka	point source, (allogenic and autogenic)	high	Focused inputs, extensive granite and gabbro catchment	high	Drainage is very focused, surrounded by steep, partly cleared, non-karst catchment, extensive soil and sediment deposits. Some forestry
	Pohara	point source (allogenic)	high	Extensive non-karst catchment, allogenic inputs	high	Drainage is very focused, surrounded by steep, cleared, non-karst catchment, extensive soil and sediment deposits

* Type of hydrological inputs associated with sedimentation: either into caves where drainage and sediment input is focused or into tight fissures where drainage and sediment inputs are dispersed.

**Qualitative assessment of risk based on present geomorphological conditions and land use. Includes non-karst catchments, which in many areas is the likely source of sediment supply and high energy flows. If an area is undisturbed then potential for sedimentation can be taken as that for natural susceptibility.

Table 7.3. Interpreted vulnerability of the karst zones to sedimentation of surface and subsurface streams as a result of human induced change.

Geomorphological group	Zone	Predominant hydrological input type*		Risk of pollution**	Reasons
predominantly autogenic	Takaka Plateau	point source (autogenic)	some non-point source	low to moderate	Lack of soil to concentrate runoff, very permeable surface, pastoral grazing
	Takaka Walkway		non-point source	low	Reserve area, low intensity landuse, (point source inputs in Summit Sink)
predominantly allogenic with low slope angles	Canaan South	point source (allogenic)		moderate	Moderate intensity of landuse around inputs, drainage very focused
	Canaan North	point source (allogenic and autogenic)		moderate	Moderate intensity of landuse around inputs, drainage very focused
	Pikikiruna	point source (allogenic)		moderate	Moderate intensity of landuse around inputs, scrub regenerating around some inputs
mixed with high slope gradients	Kairuru	point source (allogenic and autogenic)		moderate	Point source inputs largely in areas with regenerating scrub, plateau areas in pasture
	East Takaka	point source (allogenic and autogenic)		moderate	Steep slopes focus runoff, low to moderate landuse intensity, increase in population because of lifestyle development
	Pohara	point source (allogenic)		high	Moderate to high density population, some intensive agricultural and horticultural practices, increasing development, greater surface runoff,

* Type of hydrological input impacts on the rate and nature of any groundwater contamination (see text). While the natural susceptibility for pollution in undisturbed areas is regarded as low, the contamination risk to water resources remains should introduction of pollutants occur.

**Qualitative assessment of risk based on present geomorphological conditions and landuse. Includes non-karst catchments.

Table 7.4. Interpreted vulnerability of the karst zones to pollution of surface waterways and groundwater as a result of human induced change.

7.4.1 Residential development

Residential development in the inhabited areas of the karst has increased significantly in the last decade. The 2001 census figures (Chapter 2) show that in the ten years prior, the resident population in the Pohara and Takaka Hill areas has increased by 28% to 594 and 53% to 225 respectively. These figures do not account for the continuing growth in the past few years, particularly in Pohara where several subdivisions have been developed and a surge in holiday makers occurs over the summer months .

Pohara, with a mild climate and coastal aspect, is the most populous area of the karst. The character of the area has and is changing considerably, from a predominantly farming community and minor beachside holiday location with a very small permanent population, to an increasingly urban environment. Photos taken of the Pohara settlement prior to the 1960's (Takaka Public Library, Baird, J.) show only a few houses. Rapid changes to the built environment in the Takaka Region has been of some concern to local residents. In a recent survey of current issues and potential futures facing the Golden Bay area, 3 out of 4 respondents identified residential development, including the planning, location and nature of new developments as a primary subject requiring consideration (Foulkes 2002).

While land use in the Takaka Hill area has not changed considerably because of the increase in lifestyle farming blocks, the density of housing in the Takaka Hill area (Pikikiruna and Takaka Plateau zones) is changing.

Residential development and an increasing population impact on the karst system by (a) modifying the surface topography and landforms because of construction of housing and associated infrastructure, especially roads, (b) changing the rate or route of, often intermittent, surface and subsurface channels, (c) introducing sediments and/or refuse into enclosed depressions, and (d) discharging into waterways. Therefore, the most common problems likely in the Pohara and Takaka Hill areas as a result of increasing population density are pollution, flooding and ground collapse (Williams 1993, 1980). Figure 7.8 provides examples of some of the impacts.

In many cases surface permeability is reduced by compaction of the ground surface, road construction and paving, house building, and infilling of dolines or caves. The subsequent increase in flow velocity and surface runoff causes an increase in soil erosion and sediment transport rates and accelerates doline development (White 1988, Williams 1980). The natural propensity of karst to form vertically draining subsidence features, such as dolines, constitutes a significant hazard in the inhabited karst zones (Williams 1993, Ford and Williams 1989, White 1988, Beck and Wilson 1987).

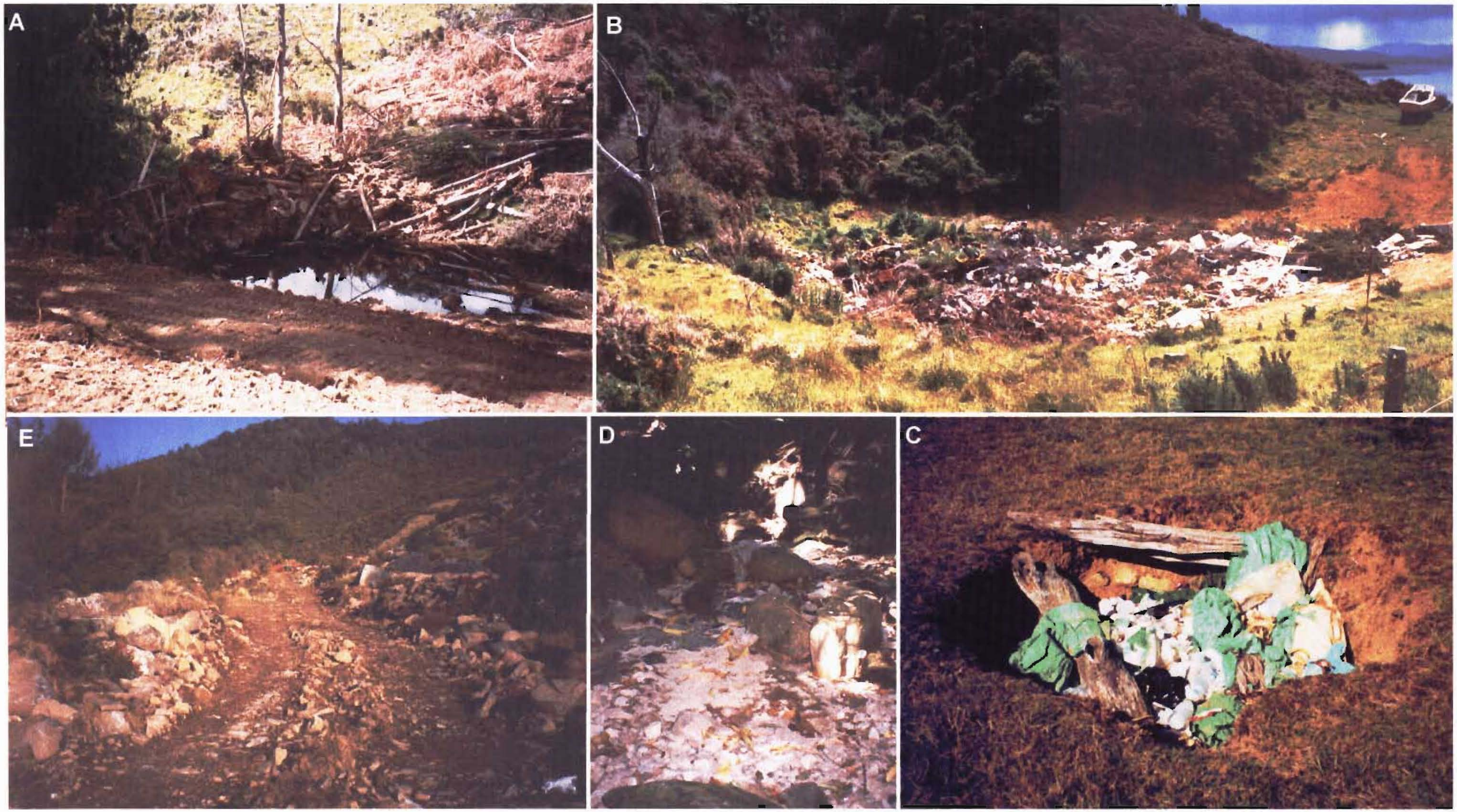


Figure 7.8. Examples of impacts on karst as a result of human activities. Clockwise from top left. (a) modification of intermittent stream channels. (b) and (c) doline rubbish dumps. (d) discharges to streams and cave streams, for example, concrete washed into stream from nearby development. (e) modification of surface landforms by construction of roading and other infrastructure.

Ground collapse is one of the most common impacts associated with urbanisation in karst areas. Subsidence of overlying sediments, which have been washed down solutional voids, is a primary cause of ground failure (Kiernan 1990).

That sediment transport is a fundamental cause of surface failure is of importance to housing developments in the study area, particularly as many homes are preferentially located on soil covered karst areas. The risk of surface collapse in the study area is reflected in the numerous accounts of the rapidly occurring (sometimes less than day) expansion of existing or sudden appearance of new dolines. Some landowners observed that collapse of unpaved road surfaces is particularly common after ground disturbance or heavy rainfalls. Downwashing of surficial material is commonly noted particularly along road verges where the runoff is focused into roadside depressions. People, particularly those home-owners with houses built in dolines, may not be aware of the potential risks related to construction in karst terrain.

A recent resource application in the Pohara karst zone (Millar 1997) provides a further example of the possible lack of awareness when considering changes to drainage or recharge. The submission requested an increase in the maximum discharge to an existing cave stream by 75%. While methods to mitigate sedimentation and contamination of the waterway were discussed, the potential for increased in-stream sediment transport, and possible ground failure was not. Recent changes in the cave system are observed. Previously, the passage near the cave entrance formed a ponded waterway, possible headward retreat of the sink, and damming and infilling of the stream channel have limited recharge to the cave. Nearby alluvial dolines, apparently related to the cave stream, show indications of active subsidence. A review of the near-cave entrance shows a recent reduction in the sedimentary deposits covering the floor of the cave passage.

Changes to groundwater are more common in populated areas, discharges to water such as stormwater runoff, refuse disposal, and leaky sewerage systems are possible sources of groundwater pollution (Table 7.4). Groundwater contamination is not only of importance to water as a resource but to its impact on instream values such as the inherent structure and form, the sediments, and fauna and flora. The high relative humidity of caves containing populations of specialised subterranean species (Chapter two) means that the cave dwelling organisms commonly found in the marble and limestone caves, including those species which are endemic to the region, are particularly susceptible to the introduction of toxins (Millar 1997).

Rubbish disposal in dolines and caves is widely observed in association with inhabited areas. The prerequisite for doline formation is the connection of the subsurface drainage to outputs such as rising streams or springs. Dolines can be considered as the headwaters of subsurface streams. Thus, while enclosed depressions make convenient rubbish disposal sites, refuse in a doline is a potential source of groundwater contamination or pollution (White 1988).

Degradation of water resources is especially important in the Pohara zone where karst waters recharge local aquifers and water supplies (Water Supply Cave, Tasman District Council water reserve). Hydrological connectivity to outputs in the limestones are unknown and the impacts of discharges to water supplies can not be assessed. The risk of groundwater contamination is highlighted by recommendations made by authors such as White (1988) and Gams et al. (1993) who state that dolines, caves and abandoned quarries must not be used as rubbish disposal sites. Gams et al., (1993, pp 83) further maintains, "It is better to choose disposal sites outside of karst areas".

7.4.2 Agriculture

Land clearance in association with agriculture, particularly at the turn of last century, resulted in widespread soil loss, sedimentation and loss of soil productivity. The dependence of people on agriculture, which in turn is dependent on the soil, makes soil related issues of primary importance to karst management (IUCN 1996).

Where farms are well established, soil erosion and sedimentation rates are likely to have stabilised under the new conditions. Further soil losses are more probable under changing land use conditions such as farm development, track building, residential development and forest harvesting. The susceptibility of the karst zones to soil erosion and sedimentation are outlined in Table 7.2-7.3.

This study did not directly measure chemical inputs, but further impacts related to farming include infilling of or dumping farm rubbish into dolines, and the contamination of water resources by livestock and agri-chemicals. Groundwater contamination is more likely where moderate to intense land use occurs in those zones characterised by allogenic or point source inputs. The impacts of non-point source pollution are limited because of all the zones, only the Takaka Walkway is particularly susceptible to diffuse inputs. Sources of non-point pollution are associated with widespread fertiliser and/or chemical (pest/weed control) applications. The likelihood of fertiliser or chemical application in a low intensity land use, reserve area is slight.

The effects of disposing farm waste into dolines are similar to that found in urban areas. Plastics, silage wraps, farm machinery and old fences are often found in dolines. Many landowners are becoming aware of the potential for water pollution from doline dumps and the practice of dumping farm chemicals in dolines is decreasing. An unavoidable part of karst farming however is the loss of stock down open crevasses and shafts, this may affect the quality of downstream water supplies.

7.4.3 *Forestry operations*

Increased sedimentation is the largest risk associated with forest activities: in the study area forest harvesting is the most likely reason for future extensive land clearance and induced sedimentation (Table 7.2-7.3). Much of the fallen timber and tree roots were left after early hand-felling of forests, and although soil disturbance was presumably slight compared to present day mechanised forestry techniques, around 10-30 cm of soil cover was eroded and transported through the karst drainage networks following land clearance.

Examples of impacts associated with present day forest harvesting are illustrated in Figure 7.9. Most of the plantation forestry blocks in the study area are located either on granitic soils overlying karst rock or on adjacent granite catchments and are therefore connected with point source drainage inputs. The harvesting of these forest plantations upon maturity is likely to cause sedimentation of the conduits and caves associated with the focused runoff. For example, forest blocks near the Canaan Road saddle occur upstream of Middle Earth Cave (Pikikiruna zone).

Increased sediment inputs are largely attributable to soil disturbance during harvesting (Ministry for the Environment 2001, Kiernan 1988). Roading, stream crossings, skid pads and logging tracks cause a significant increase in sediment yields. Sediment yields associated with forest harvesting can increase by up to 42% following cable logging or 700% from skidder logging, relative to pre-disturbance levels (O'Loughlin 1980, cited in Ministry for the Environment 2001). Soil mass movements on steep, recently cleared land are 2 to 40 times more common than on land under forest cover (Sidle et al. 1985).

7.4.4 *Quarrying*

Economic-scale quarrying sites are limited to the Tarakohe (inactive since closure in 1988) and Ngarua Quarries, located in the Pohara and Kairuru karst zones respectively (Chapter two). Carbonate rock extracted from the quarries is utilised in a wide range of industries and quarries are valued for their contribution to local economies.

The quarries are clearly seen in Figures 4.2 and 4.5, particularly because the light coloured, recently exposed carbonate rock surfaces are conspicuous against the surrounding background. The Tarakohe Quarry (Pohara zone) is located in a low lying, gently inclined valley close to the coast between Pohara and Ligar Bays. Many of the faces in the quarry are near vertical and the enlarged floor of the quarry lies close to sea level. The quarry site remains un-rehabilitated. The Ngarua Quarry, and the smaller, adjacent Kairuru Quarry (Kairuru karst zone), are located in the steeply-sloping side walls of Holyoake Valley.

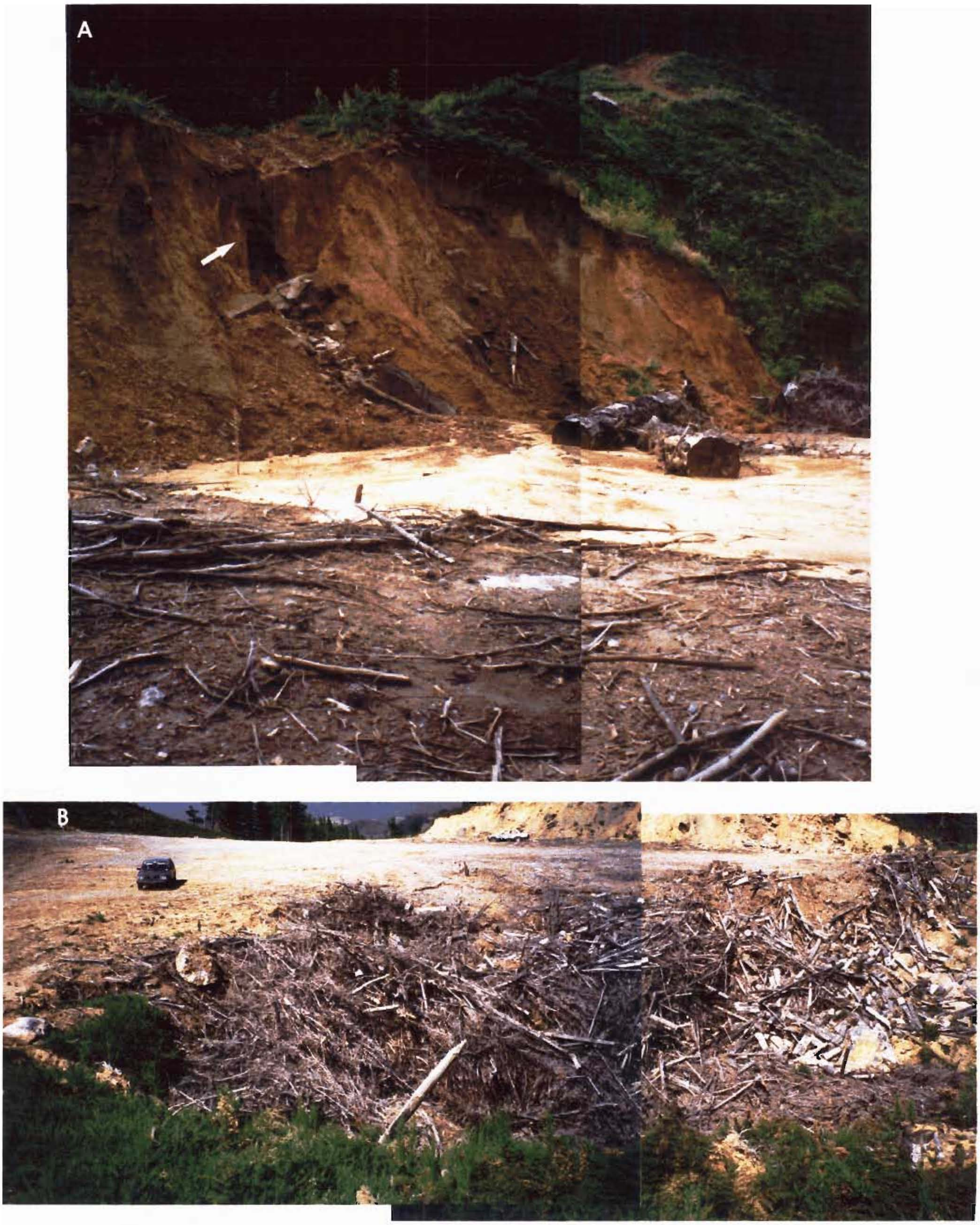


Figure 7.9. Effects of forestry harvesting showing soil erosion, sedimentation and infilling of dolines (East Takaka). (a) Rill erosion of forestry track and sedimentation of non-calcareous soils. The opening marked with an arrow, in which rundkarren is being exposed, is progressively enlarging providing a good example of potential ground failure. (b) Infilling of dolines with logging debris. Large cracks - surface openings are appearing around the perimeter of the doline indicating subsidence.

Removal of material in the, now closed, Marble Acre Quarry (Canaan South) has resulted in the destruction of a limited part of a karst pavement, which hosts well-developed examples of horizontal solutional forms including tritt- and meanderkarren.

The main impacts of quarrying on karst systems is landform modification and destruction (Gams et al. 1993). Rates of rock removal from the quarry sites occur at a far greater rate than in the natural environment. For example, the approximately 70-80m removed in the last 100 years during production at Tarakohe (the surface extent of which is no more than 1km^2) contrasts significantly to the 8mm /100 years of surface rock mass removed by solution in the Riwaka Basin (Williams 1982). The impact of quarrying on the geomorphological attributes of the karst system in the study area are constrained by the limited size and number of quarrying operations in relation to the overall karst system and the local landforms. Gunn (1993) notes however, that the seriousness of the impacts to karst is related more to location than to size, with impacts varying on whether the quarry is situated on flat ground, into valley sides, or into a hill. The quarries in the study area are presumably, situated in valleys because of the ease associated with quarrying scarps and cliffs rather than flat lying surfaces. Observed impacts of quarrying in the valleys includes (a) valley side steepening or the creation of scarps caused by cutting of quarry faces, (b) removal of overlying deposits, such as the Tarakohe Mudstone, and (c) widening of the valley floor due to the removal of rock mass and the creation of benches (Gunn 1993). The resultant anthropogenic landforms in the smaller quarries, such as steep scarps and wider valley floors are similar in form and scale to those found naturally, hastening natural rehabilitation of these quarries.

The destruction, modification or infilling of caves may also result from mining operations (Gunn 1993). Both quarry areas are cavernous, and there are accounts of cave systems altered or destroyed during quarrying.

More inconspicuous impacts include the removal of the upper drainage zone (the epikarst or subcutaneous zone), and the introduction of waste waters to subsurface drainage systems. To date, hydrological connections have not been established for inputs at the quarries and thus, changes to subsurface connections by modification of surface recharge zones or discharges to the output streams can not be assessed. Some residents in the Pohara area have concerns regarding an old landfill site in the quarry area, and polluted waters resurging on Pohara Beach.

7.4.5 Tourism and Recreation

As most of the area is private land and public access is restricted, the impacts of tourism and recreation are limited to areas designated for open access. Visitor access in the study area is largely confined to tourist caves such as Ngarua and Rawhiti Caves, Conservation Estate areas including Harwood's Hole, Rameka Track, Riwaka Resurgence, and covenanted reserves such the Takaka Walkway and The Grove.

Wear and tear of solution sculpted forms and/or compaction of soils appears to be the major impact from visitors to the surface karst areas. The Grove, Takaka Walkway, Riwaka Resurgence and Harwood's Hole are popular sites for viewing karst landforms as indicated by the number of cars present during field mapping of these features. Tracks in the Takaka Walkway and to Harwood's Hole are well designated and deviation from the marked paths appears limited. Visitors to The Grove Scenic Reserve however, are less likely to follow pathways (which are less delineated) and the corridors developed in grikes appear to form appealing diversions, with the resultant compaction of the calcareous soils by trampling.

Visitors to the Harwood's lookout clambering over sharpened surfaces have inadvertently destroyed some well-developed exposures of rillenkarren. Some graffiti is present and litter is noted in grikes between the outcropping blocks. Grikes and dissected karren forms have been broken and rocks are commonly thrown into doline entrances and shafts. While these impacts have a limited impact on the karst system as a whole, they do contribute to the aesthetic degradation of the sites.

Cave visitation can be divided into two groups; caves with restricted, limited or open access which are mainly used by recreational cavers, and tourist caves (New Zealand Speleological Society 2003). Recreational or wild caving is often carried out in association with the New Zealand Speleological Society, who promote cave protection through the use of an ethical guideline (online reference; www.massey.ac.nz/~sglascow//nzss/ethics.htm). Tourism impacts on the caves include wear and tear of caves surfaces and vandalism of caves features such as stalagtites and stalagmites (Baird, J. *pers. comm.* 2003). Changes to cave environments also occur because of body heat, respiration and lighting (Huppert et al. 1993). A review of these impacts and the associated management strategies are beyond the scope of this study, however studies in an international context include the IUCN Commission on National Parks and Protected areas (1996) and Huppert et al. (1993). Tourism and caves, and cave management in New Zealand is discussed by the Department of Conservation (1999) and Williams (1987).

The positive effects of tourism and recreation in areas of the 'Marble Mountain' and Takaka Valley, including the opportunities for education and advocacy regarding the distinctiveness and vulnerability of karst, are important to acknowledge.

7.5 Summary assessment of karst vulnerability

Human induced changes have significantly altered the natural environmental systems and anthropogenic processes have become increasingly pervasive since people settled the karst terrain around 100 years ago. The most widespread impacts in the karst are firstly, soil erosion and sedimentation resulting from land clearance, secondly, water quality degradation occurring because of increased sediment yields and discharges to waterways, and thirdly, landform modification or destruction because of housing, roading, and quarrying. The vulnerability of the zones to human induced impacts, is dependent on the inherent characteristics of the zones which in turn is related to the predominant landforming processes. The type of land use influences the susceptibility of the zones, and the risk of human impacts increases with higher population densities.

Assessments of soil erosion show that around 10-30cm of soil has been lost in most zones, representing a significant change to the karst systems. Because of the naturally thin rendzic soils and high potential for downwashing, the zones of the autogenic group (Takaka Walkway and Takaka Plateau) are the most vulnerable to soil erosion. The diffuse autogenic recharge, non-point source drainage, and low angle slopes limits the risk of sedimentation and sediment-associated water quality problems.

Because of the focused runoff, conduit flows and relatively extensive non-calcareous soil and sediment deposits, the zones of the allogenic or mixed groups are most vulnerable to sedimentation and deterioration of water resources.

CHAPTER EIGHT – CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary conclusions

8.1.1 Geomorphological analysis

Observable and quantifiable differences in the geomorphology of the karst zones are used to differentiate the karst in the study area into eight karst landform assemblage zones: seven in the uplifted Arthur Marble uplands and one in the low lying, coastal Takaka Limestones. Mapping of the karst zones was important in fulfilling the first objective of this thesis: to identify and understand the karst systems.

Kairuru karst zone is characterised by narrow, elongate plateaus, and south-easterly trending karst valleys, including the large v-shaped Holyoake Valley.

The *Takaka Plateau zone* forms an undulating land surface at around 600m and is considered very scenic for its large well-shaped solution dolines and uvalas, and sculptured rock outcrops. Recognised as a karst feature of national importance, the zone is distinguished by a lack of surface waterways.

Located in a shallow basin, *Canaan South zone* is characterised by rolling sediment-covered downlands, with fluvial landforms, and alluvial dolines. Recognised as a border polje, the Canaan South zone is registered as a feature of regional importance.

Canaan North zone, dominated by a large linear, u-shaped dry valley, extending south-westwards from the Wainui Saddle to Harwoods Hole, includes Harwood's Hole, the deepest free-fall tomo in New Zealand. The now dry valley floor is scattered with numerous small alluvial and solution dolines.

Extensive surficial cover, rolling topography, and alluvial dolines typify the *Pikikiruna zone*. Characterised by non-calcareous soils and blind valleys, the Pikikiruna zone hosts several extensive cave systems.

The *Takaka Walkway zone* is distinguished by the fractured and brecciated appearance of the marble, the high density of collapse dolines (or tomos) and outcropping marble. The zone, with increased permeability caused by the high density of fractures, has very diffuse autogenic recharge.

Characterised by westerly draining, incised, v-shaped, karst gorges with interconnected ridges, the *East Takaka zone* includes marble scree slopes and sinking allogenic streams. Several, small, doline-dotted plateau surfaces occur between the large gorges.

The *Pohara zone* is characterised by coastal and alluvial terraces, and outcropping ridges dissected by runoff from the adjacent granites and overlying Tertiary sediments. Cliffs and knolls are distinctive of the limestones. Lithological heterogeneity has resulted in relatively high numbers of grikes and kamenitzas.

8.1.2 Landforming processes

Tectonic uplift, climate and structure, which are important controls on evolution of the karst in the study area do not account for the differences in the karst zones. The most influential factors on landform development in the karst zones are the interacting allogenic or autogenic denudational systems, soil or sediment cover and surface slope gradients. Based on the predominant landforming processes, the zones are divided into three types;

1) Predominantly autogenic.

Solution is the dominant process in this group (Takaka Walkway and Takaka Plateau zones) and most of the drainage is underground. The undulating plateaus reflect the uniform surface lowering accomplished by autogenic recharge. These zones support well-developed epikarst. The largely exposed karst surfaces, hosting numerous dolines, are widely recognised for their visual impact. Rendzic soils are common.

2) Predominantly allogenic with low angles slopes.

Karst valleys, caves and allogenic soils, common in the zones in this group (Canaan South, Canaan North and Pikikiruna zones), occur because of combined fluvial and solutional processes and concentrated allogenic inputs. This group is characterised by low angle slopes and largely enclosed basins resulting in the aggradation of non-calcareous sediments and lateral planation of the karst valleys.

3) Mixed denudation systems with higher slope gradients.

The karst valleys and gorges in this group reflect fluvial processes and focused allogenic drainage. The steeper slope angles in the East Takaka, Kairuru and Pohara karst zones have resulted in overland flow, lateral solution and vertical incision. Vertical epikarst development is largely restricted to the plateaus and areas with lower slope angles. The distribution of dolines is correspondingly limited. Autogenic recharge is becoming more prevalent as incision and headward retreat isolates allogenic inputs. The soil type and cover is variable reflecting the intermediate denudation systems.

The Pohara karst zone is distinct from the marble karst zones in that sea level changes and the action of coastal processes have produced coastal karst forms and enhanced cliff development.

8.1.3 Assessment of human induced changes and environmental impacts

The recognition of the karst zones and the main landforming processes was an important means of evaluating human induced change and anthropogenic impacts (as outlined in the second objective of this study). Changes to the karst by people have significantly altered the natural karst systems with anthropogenic processes becoming more pervasive with increasing development. Features of the karst, including soils, waters, landforms, and subsurface systems are the resources that people depend on for a wide range of land uses including agriculture, tourism, forestry, or simply a place to live. It is these resources that are impacted upon by the often indirect anthropogenic changes.

Land use influences the susceptibility of the zones, with higher population densities increasing the risk of human impacts. The vulnerability of the karst zones to human induced impacts is not only dependent on land use but on the inherent characteristics of the zones which in turn is related to the predominant landforming processes. Just as the attributes of the karst are different in each of the zones so is the susceptibility to change. A summary of the vulnerability and susceptibility of the karst zones to soil erosion, sedimentation and water quality degradation is presented in Figure 8.1.

Because of the naturally thin rendzic soils and high potential for downwashing, the zones of the predominantly autogenic group (Takaka Walkway and Takaka Plateau) are the most vulnerable to soil erosion. Soil assessments in these zones show that 10-30cm of soil has been eroded following land clearance c. 100 years ago. The diffuse autogenic recharge, non-point source drainage, and low angle slopes lower the relative risk of sedimentation and sediment-associated water quality problems.

Focused runoff, conduit flows and relatively extensive non-calcareous soil and sediment deposits, mean that the zones of the allogenic and mixed drainage groups are most vulnerable to sedimentation and deterioration of water resources. Because of increasing development and relatively intensive land use, the Pohara zone is the most at risk of karst degradation (Figure 8.1).

Natural susceptibility (unaltered natural environments) | **Susceptibility in areas already cleared or modified**

Relative susceptibility

low | moderate | high

Soil Erosion
The areas with the highest risk of soil erosion are those zones with;
(i) steeper slopes
(ii) high density of surface structures and increased vertical permeability
(iii) naturally thin soils

Sedimentation
Zones with a higher susceptibility to sedimentation are those with;
(i) extensive soil or sediment deposits
(ii) focused runoff

Contamination of water
The areas with the highest risk of water quality degradation are those zones with:
(i) an increased risk of sedimentation
(ii) increased land use or higher population density, particularly adjacent to stream sinks

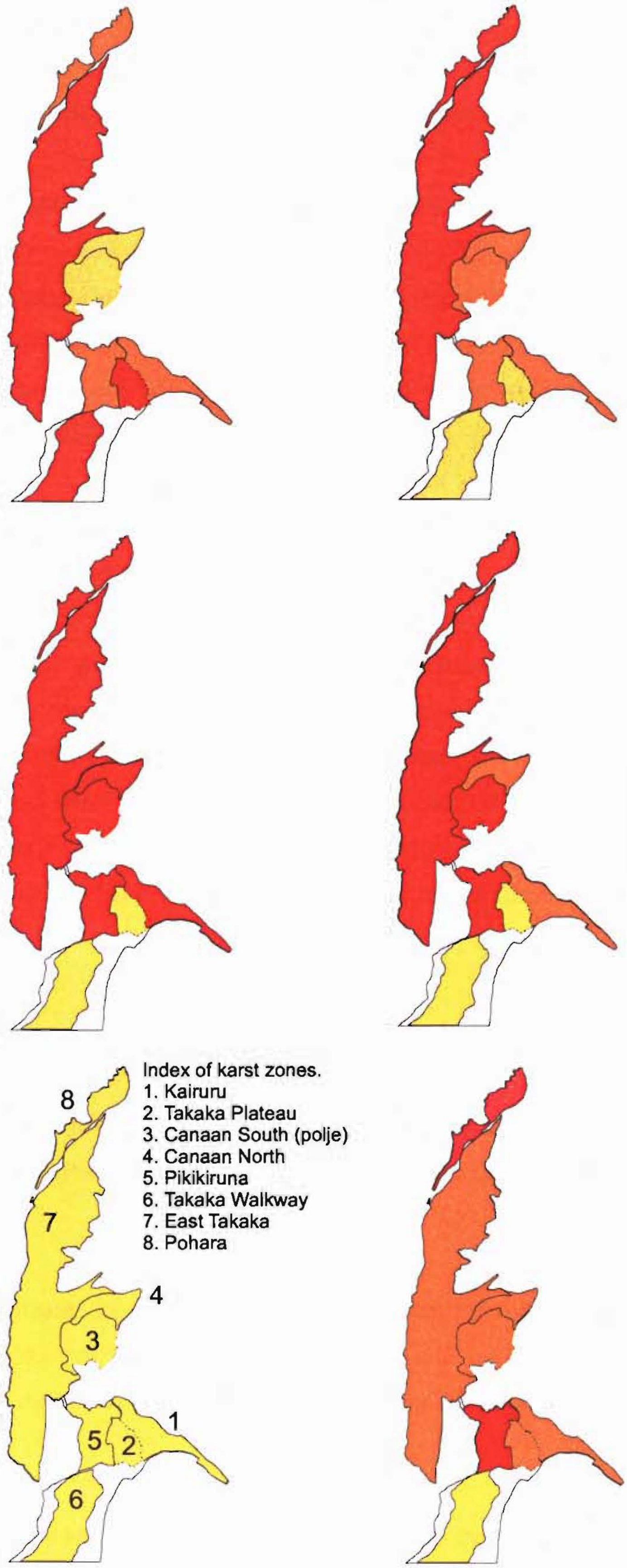


Figure 8.1. Summary of karst susceptibility. While all karst environments are highly vulnerable, the susceptibility (in unaltered and modified areas) to soil erosion, sedimentation, and water pollution is different in each of the karst zones. See text for discussion.

8.2 Limitations and recommendations for further work

During compilation of this thesis it has become apparent that there are several areas relating to environmental impacts requiring further research. Increased confidence in the results could have been achieved by:

(a) extending the systematic mapping into unaltered karst areas and further sampling of natural karst environments.

(b) examination of natural and accelerated rates of calcareous and rendzic soil erosion in the remaining karst zones to determine the controls of soil erosion in each zone.

(c) quantitative studies of rates of sedimentation and geochemical 'fingerprinting' of sediments using Caesium 137 or other tracers, allowing for better prediction of sediment source areas.

(d) sampling of surface waterways and resurgences during high flow events for water quality investigations and detailed analysis of existing water quality data.

While some elements of the karst hydrology are known, further research directed at karst systems could better examine changes to the surface and subsurface drainage networks. There is a lack of information regarding internal catchments, input to output connections, throughput rates and storage, particularly in the Pikikiruna Ranges and Takaka Limestones. Delineation of the internal drainage divides and investigation of the hydrological connectivity would complement earlier work by Dowling (1974) and allow for a greater understanding of water quality issues.

8.3 Concluding statements

This study emphasises that the Takaka and Riwaka karst areas are inherently susceptible to change and human induced impacts can affect the karst systems very rapidly after the human activity occurs.

The karst zones are effective management tools allowing better control of monitoring programmes and derivative studies including environmental surveys, site or resource planning, and hazard assessment. The establishment of a karst inventory provides useful baseline information for future work.

It is crucial that people's awareness of the karst terrains and characteristics: the surface to subsurface connections and distinct hydrology, is increased. Any education aimed at highlighting impacts should include information regarding direct and indirect effects. This is particularly important as other studies in karst areas (Huppert et al. 1988), have shown that most people feel that they are not the source of what they perceive as moderate to serious soil erosion and water quality problems.

Present management plans do not consider the differences in the susceptibility of karst areas to impacts. Increased protection of the karst requires (a) sampling programmes that take into consideration the unique karst attributes and (b) implementation of long term monitoring in unaltered and altered karst environments to provide background rates and induced rates of change. Reducing the impacts on the Takaka and Riwaka karsts requires an increased focus on stream sinks and allogenic catchments. Protection of these areas by forestation, land retirement or riparian planting may help to avoid future sedimentation or groundwater contamination problems.

GLOSSARY OF SELECTED KARST TERMS

Allogenic recharge input of water derived from neighbouring or overlying non-karst rocks, which have then drained into a karst aquifer (White 1988).

Alluvial Doline found in areas where alluvium or other sediments cover the karst bedrock. The dolines are normally shallow and bowl-shaped with the doline developing primarily in the overlying surficial material. Corrosion of the bedrock underneath the cover creates piping along enlarged joints and fractures allowing the sediment to subside into the openings by a combination of solution and downwashing (Sweeting 1973).

Autogenic recharge where the waters are derived solely from precipitation falling on karst outcrops (Ford and Williams 1989).

Blind Valley Solution of the limestone in the bed and banks of a river enlarges joints and bedding planes, which will in time absorb all water from the stream and the river will dry up. River valleys, closed at their lower ends by disappearing streams are known as blind valleys (Sweeting 1973).

Cave A natural underground cavity that connects with the surface, contains a zone of total darkness and is large enough for human entry (Forest Practices Branch 2002).

Carbonate rock rock comprising more than 50% carbonate minerals, such as calcite and dolomite

Clint block isolated between grikes, often hosting smaller karren forms (Ford and Williams 1989)

Collapse doline are often vertically walled and have a small surface plan area relative to depth. Toppled collapse boulders at the bottom of the vertical shaft indicate active collapse dolines. The main cause for formation is the collapse of a cave roof near to the ground surface (Sweeting 1971, Jennings 1972). Collapse dolines in New Zealand are commonly referred to as *tomos*. Harwoods Hole is a local example of a collapse doline.

Conduit a subsurface water course, important in the storage and transportation of water.

Corrasion mechanical weathering and removal of the rock mass.

Corrosion weathering and removal of the rock mass by solution.

Doline an enclosed depression of small to moderate dimensions, locally referred to as a sinkhole (Sweeting 1973)

Dry Valley The completely dry downstream continuation of a blind valley or engulfed stream (Sweeting 1972).

Denudation weathering and transportation of rock mass.

Ephemeral stream A stream (or portion of) that is transient, flowing only in direct response to precipitation and drying up shortly after the precipitation ceases.

Epikarst The weathered zone at the top of the bedrock, underneath the soil where solutional attack, which is more aggressive near the surface, widens joints and fissures. This upper part of the percolation zone (also known as the subcutaneous zone) has significant storage (Williams 2001).

Gorge Small allogenic streams sink almost immediately they encounter karst, whereas larger streams can penetrate well into the karst before flowing underground, and even bigger rivers never sink but run through karst areas incising deep gorges. These tend to be antecedent rivers that have maintained their course by their rate of downwards incision keeping pace with the rate of regional tectonic uplift. Thus the gorges they produce are not karst landforms but are fluvial landforms (Williams 2001).

Grike (see kluftkarren).

Headwall Cliff or escarpment commonly marking the downstream point of a blind valley.

Intermittant spring A karst spring with a transient flow, fed by a subterranean water course in which flows are only present when the subterranean cavities are full (Sweeting 1973).

Kamenitza (also known as solution basin) occur where the water collects in pools as a result of the surface being near horizontal. The stagnating water enlarges the basin by solution creating a rounded or oval pan with steep sides and a flat bottom.

Karren small scale solutional sculpture (Jennings 1971).

Karst is terrain in which relatively high rock solubility and the development of underground drainage combine to form distinctive surface and subsurface landforms (Jennings 1971). The word is also used adjectively to refer to rock, water, streams, caves and other features making up such landscape.

Karstification The processes of solution and underground infiltration where the surface features and subsurface drainage network of a karst system are developed (Sweeting 1973).

Kluftkarren (also known as grikes) form along existing joints or fracture, being the principal drains to the epikarst, dolines or surface discharge. Kluftkarren are usually seen in the field as open and enlarged fractures or clefts cut by solution into karst bedrock (Sweeting 1973, Ford and Williams 1989).

Meanderkarren develop on gently inclined surfaces where the flowing water corrodes a wandering or meandering channel.

Phreatic The water-saturated zone below the water table (White 1988).

Polje fluviokarst valley with steeply rising marginal sides, a flat valley floor covered in sediments.

Ponor (see sink).

Pocket Valley is the reverse of blind valleys, occurring in association with large springs that resurge at the foot of a limestone massif (Sweeting 1971).

Resurgence underground stream that emerges at the surface.

Rillenkarren are finely sculptured solution runnels with rounded troughs and sharpened ridges. They are usually 1 to 2cm deep, 1 to 2cm wide and less than 50cm long. They are commonly observed in groups, developing near the crest of the karst outcrop with the rills diminishing downslope. Rillenkarren form on exposed surfaces and can develop very quickly relative to other karren, appearing within a few years or even months (Sweeting, 1972).

Rinnenkarren form under exposed conditions and have rounded troughs and sharpened crests. Larger than rillenkarren, they can occur up to 40cm deep, about 10 to 40cm wide and with varying lengths from centimetre to metre scale (Sweeting, 1972).

Rundkarren develop under cover, in the presence of soil or dense vegetation. These sub-aerial drainage features are similar in size to rinnenkarren but contrast to the sharp-rimmed rinnenkarren in that the troughs and crests are always smooth or rounded (Sweeting 1972, Ford and Williams 1989).

Semi-blind Valley where waters are diverted underground for much of the time but resume downstream surface flows during times of high rainfall (Trudgill 1985).

Sinkhole refer to doline.

Sink Denotes the location of a stream disappearance (Sweeting 1972).

Spring (see resurgence) underground stream that emerges at the surface.

Solution doline often funnel shaped with an approximately equal depth to width ratio (Jennings 1971). They are formed by the focused solution of karst rock around a favourable point such as a master joint set or fracture. The removal of a greater amount of rock from the centre of the doline than from the sides gives the solution doline its characteristic morphology. If the focus of drainage is maintained the doline will concentrate runoff and further its own formation (Jenning 1972, Ford and Williams 1989).

Solution basin (or pan) see kamenitza.

Spitzkarren are similar to rinnenkarren but with very peaked crests.

Styolites are sutures in the rock where pressure solution has taken place, often leaving thin laminae of insoluble materials.

Suffusion doline refer to alluvial doline.

Through valley (or allogenic) valleys occur when rivers crossing the karst have sufficient volume to maintain flows across the surface to the output boundary (Ford and Williams 1989, Sweeting 1972).

Tomo refer to collapse doline.

Trittkarren resemble heelprints with an arcuate form and flat tread opening in the downslope direction (Sweeting 1972, Ford and Williams 1989).

Uvala are hollows or compound dolines where the floors of the depression are made up of more than one doline (Sweeting 1972).

Vadose The subterranean, unsaturated region or zone above the water table (White 1988).

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APPENDIX A – GEOMORPHOLOGICAL CLASSIFICATION DATABASE

The geomorphological classification database for each of the eight karst zones is presented below.

Common abbreviations used include:

For doline type:

Sol	- solution
All	- alluvial
Col	- collapse
Uva	- uvala
Und	- undetermined

For doline morphology:

Ass	- asymmetrical surface form
Sym	- symmetrical surface form
Irr	- irregular surface form

For karren type:

Rund	- rundkarren
Rinn	- rinnenkarren
Rill	- rillenkarren
Kamen	- kamenitza (solution pan)
Spitz	- spitzkarren
(grike	- grike)

Other:

Fract	- fractures/structural features
Jt(s)	- joint(s)
C.S.T	- cut standing trunk
Sed't	- sediment
Oma	- Ordovician Arthur Marble
Ks	- Separation Point Granites

Karst Zone	Sample	Easting	Northing	Strike/dip	Fracture Frequency						Dip			Slope	Slope
	No				1	2	3	4	5	6	1	2	3	Gradient	aspect
Kairuru	1	2503780	6021347	094/64E	5	0	0	2	5	2	40	40	60		22
Kairuru	2	2504458	6021352	276/78S	1	3	0	3	1	2	68	68	40	54	24
Kairuru	3	2504590	6021347	090/52S	1	2	3	0	2	3	70	44	70		6
Kairuru	4	2504451	6021668	112/70S	2	0	0	4	2	1	16	80	32		
Kairuru	5	2503392	6021498	284/80S	3	3	0	1	3		12	76	44		16
Kairuru	6	2504067	6021494		4	0	2	0							20
Kairuru	7	2503770	6021664	080/76S	4	6	0	2	2		75	12	8		12
Kairuru	8	2503548	6021811	092/60S	5	6	2	6	5	2	24	60	46		14
Kairuru	9	2503552	6021959												35
Kairuru	10	2503341	6021960												
Kairuru	11	2503333	6021811	090/52S	2	4	4	1	1		50	16	65		2
Kairuru	12	2502944	6022268	144/88S	8	2	3	1	3		18	65	20		46
Kairuru	13	2502762	6022272												30
Kairuru	14	2502750	6022116	140/70SW	1	2	0	4	2		75	32	30	36	36
Kairuru	15	2502885	6022123		2	5	2	3	0						28
Kairuru	16	2502934	6021974	124/64NE	2	0	3	1	2		20	20	45	28	50
Kairuru	17	2502735	6022585												20
Kairuru	18	2503121	6022578												25
Kairuru	19	2503336	6022418	120/50S	3	3	0	2	1		40	30	88	20	40
Kairuru	20	2503550	6022263		0	0	0	0							42
Kairuru	21	2503562	6022570		0	2	2	2	0		10	64	40		32
Kairuru	22	2503791	6022407												18
Kairuru	23	2504007	6022251												
Kairuru	24	2504228	6022095		0	0	1	0			28				30
Kairuru	25	2504229	6021804												28
Kairuru	26	2504342	6021585												
Kairuru	27	2502870	6021369	288/60S	1	1	0	3	3	1	28	18	20	26	32
Kairuru	28	2502883	6021518		1	0	2	1	0		24	18	40	20	42
Kairuru	29	2502746	6021683												
Kairuru	30	2503156	6021370		1	1	0	2	0	1	10	45	28		
Kairuru	31	2503331	6021507	084/80SE	1	1	1	1	0	2	80	86	30		6

Karst Zone	Sample	Vegetation	Deforested	Doline Type						Strike	Associated landform
	No	type		Type	Morp	Size(m)	Type	Morp	Size	axis	
Kairuru	1	pasture	y								
Kairuru	2	pasture/regenerating shrub	y								
Kairuru	3	pasture/shrubs/bracken	y								
Kairuru	4	pasture/regenerating shrub	y	Sol	Ass	10-5				108	doline field
Kairuru	5	pasture/regenerating shrub	C.S.T	Sol	Ass					175	local sink doline
Kairuru	6	pasture/regenerating shrub	y								
Kairuru	7	pasture/regenerating shrub	C.S.T	All	Ass	5				108	valley side
Kairuru	8	pasture/shrub	C.S.T	All	Irr	2-3					valley side
Kairuru	9	pasture/regenerating shrub	C.S.T	Sol	Ass	80-100					blind valley
Kairuru	10	pasture/regenerating shrub	y	Sol	Ass	10-2				098	doline
Kairuru	11	pasture/regenerating shrub	C.S.T								
Kairuru	12	regenerating shrubs/bracken	C.S.T								
Kairuru	13	regenerating shrubs/bracken	fallen logs								
Kairuru	14	pasture/bracken	C.S.T	Uva	Irr	2-20	Sol				
Kairuru	15	grasses/bracken	C.S.T								
Kairuru	16	bare karst/some fauna in fract/grikes	y								
Kairuru	17	pasture/bracken	C.S.T								
Kairuru	18	pasture	C.S.T	Sol	Ass		All	Ass	2-10		valley, doline field
Kairuru	19	pasture/bracken	C.S.T								
Kairuru	20	regenerating bracken/shrub	y								
Kairuru	21	bracken, grasses	y								
Kairuru	22	bracken, grasses	C.S.T	Und	Irr	3-4					dry valley
Kairuru	23	gorse, bracken	y								
Kairuru	24	gorse, grasses	y								
Kairuru	25	gorse, grasses	y								
Kairuru	26	pasture/regenerating shrub	y	Sol	Ass	5-30				360	ridge top
Kairuru	27	pasture/regenerating shrub	fallen logs								
Kairuru	28	pasture/regenerating shrub	y								
Kairuru	29	pasture/regenerating shrub	fallen logs								
Kairuru	30	pasture/regenerating shrub	fallen logs								
Kairuru	31	pasture	fallen logs	Sol	Ass	3-8	All	Ass			interridge-dry valley

Karst Zone	Sample	Karren type										Macro landform	Comments
	No	Type	Size(cm)	Length(m)	Other	Type	Size	Length	Type	Size	Length		
Kairuru	1	rund	20-30	<1.0								dry valley	sloping hill leading to Holyoake Stream
Kairuru	2	rund	10-30	<0.5	jts enlarged	rinn						dry valley	sloping hill leading to Holyoake Stream
Kairuru	3	rill	3-4	<1.0	well formed in	rund	15	<1.0				dry valley	leading to Holyoake Stream
Kairuru	4	rund	10-15	~1.0		rinn						dry valley	leading to Holyoake Stream, steep sided doline, thin soil cover
Kairuru	5	rill	6-8	<1.0		rund	10-40	<1.0				valley ridge	very coarse crystalline Oma, doline is sink for local downhill overland flow, strike of ridge follows bedding
Kairuru	6	rund			subcropping							valley ridge	poss not insitu
Kairuru	7	rund	5-20	<1.0	mod-poor							dry valley	dry valley side, scattered outcrop only
Kairuru	8	rill	3-4	<1.0	scattered	rund						dry valley	variable fract direction, karst appears relatively clastic
Kairuru	9											blind valley	dolines lining up in minor valley subsidiary to and parallel to main valley, well shaped dolines
Kairuru	10	rund			mod formed							doline	steep sided doline in valley centred on saddle between two peaks, scattered outcrop only
Kairuru	11	rinn	15-20	<1.0	getting sharper							ridge	small outcropping ridge aligned parallel to tow dry/blind valleys, poss spitzkarren
Kairuru	12	rund			poorly							blind valley side	some rounding of karst surfaces, very flaggy, dirty appearance, thin soil cover
Kairuru	13											blind valley	incr soil cover downslope, fine, med yllw brn soils, coarse sand clasts, outcropping karst on ridges
Kairuru	14	rund	40	<1.0	dirty pk Oma							uvala	poss juvenile abandoned sink/doline location, thin soil cover with karren outcropping on ridges and valley sides
Kairuru	15	rinn	10-30	<1.0	mod formed							slope	appears some collapse of blocks, surface predominantly outcropping, subcropping karst at ridge top
Kairuru	16	rill	5-6	<0.5	well formed	kamen	20-30	0.15	grike	20-30	<2	ridge	probable soil erosion, tree roots, also spitzkarren, rundkarren and rinnenkarren
Kairuru	17											dry valley	side of vlly, exposed ridges of karst, incr soil downslope, very small depressions, poss tree fall hollows
Kairuru	18	rund			where exposed	rinn						blind valley/doline field	doline field, blind valley leading to larger valley, apparent sed't layer, looking at outcrops of karst, Ks to North of field
Kairuru	19	rill	5	<0.7	developing	rinn	50	<2.0	rund			dry valley	ridge, erosion of soil
Kairuru	20	rill	5	<0.5	developing	rund			rinn			dry valley	intermittent flow, some impurities in karst, org coloured, large outcropping blocks in valley side
Kairuru	21	rill	6-7	<1.0	well formed	rund	20-30	~1m	rinn			dry valley	rich brn soils - autogenic?, below ridge in dry valley
Kairuru	22											dry valley	with subsidiary valley to side, ,ay have higher fan sed'ts or sed't from soil mov't on higher slopes
Kairuru	23											dry valley	close to contact, buried karst, next to dry valley, qtz, Ks boulders alluvial sed'ts, intermittent flow
Kairuru	24	rund	10-12	1-2	well-mod	rinn						dry valley/canyon	sides of valley large thickness cover 2-3m karst outcrops scattered on slope, allogenic drainage
Kairuru	25											canyon side	soil covering karst, slope shrub covered, soil thickness 1m at least, brn yllw fine-med soils
Kairuru	26	rund			where exposed	rinn						plateau (minor)	dolines aligned on ridge top between large canyons, poss almost polygonal karst
Kairuru	27	rill	5-10	<0.5	mod formed	rinn	10-30	<1.0				karst canyon	thin soil cover throughout, karst and karst toppled blocks (some collapse) scattered
Kairuru	28	rund	10-20	~1-2	well formed	rinn						dry valley/canyon	numerous toppled blocks on valley walls and floor, very steep canyon, thin soils
Kairuru	29	rund	10-20	<1.0								dry valley	fallen blocks, varying degrees of karren formation
Kairuru	30	rill	5-8	<1.0		kamen	20	<0.05	rinn	10-30	1-2	dry valley ridge	blocks toppled, varying karren development
Kairuru	31	rinn			poorly formed	rund						dry valley ridge	interridge alignment of dolines in valley, bowl and steep sided sed't filled dolines

Karst Zone	Sample	Easting	Northing	Strike/dip	Fracture Frequency						Dip			Slope	Slope	Vegetation	Deforested	Doline Type						Strike	Associated landform
	No				1	2	3	4	5	6	1	2	3	Gradient	aspect	type		Type	Morp	Size	Type	Morp	Size	axis	
Takaka Plateau	1	2501039	6020758	308/60NE	4	2	5	2			50				8	regenerating shrub	y								
Takaka Plateau	2	2501196	6020850		4	3	3	4	6						10	pasture	C.S.T	Sol	Ass		Uva	Ass	90	002	uvala
Takaka Plateau	3	2501446	6021196		3	4	3	2			44	50			10	bracken	y	Sol	Irr	3-4					basin
Takaka Plateau	4	2501603	6021200													pasture	fallen logs	All	Sym	5-10					basin
Takaka Plateau	5	2501746	6021227	106/64S	3	3	1	7								pasture/regenerating shrub	y								
Takaka Plateau	6	2501727	6021439	222/82E	3	2	2	2	5		26				14	pasture/regenerating shrub	y	Sol	Ass	15				040	
Takaka Plateau	7	2501899	6021237	084/30N	6	3	5	1	6		54				8	bracken	y								
Takaka Plateau	8	2501740	6021508		2	3	3	6	2						26	bracken	y								
Takaka Plateau	9	2501687	6021671	270/76N	2	2	4	5	3						12	pasture	fallen logs	Sol	Irr	5-15					blind valley
Takaka Plateau	10	2501981	6021711	098/98S	4	5	1	2	3						14	pasture/regenerating shrub	C.S.T	Sol	Ass	20-	Uva			176	uvala
Takaka Plateau	11	2502213	6021904		2	0	6	12	4						20	bracken	y	Uva	Ass		Col			078	ridge/basin
Takaka Plateau	12	2502081	6022173	096/76N	7	6	8	3	1		78				10	bracken	y	Sol	Ass					110	hill slope leading to uvala
Takaka Plateau	13	2501925	6022140	104/80NE	2	4	2	2			58				4	bracken	y								
Takaka Plateau	14	2501813	6021910	086/58S	2	0	2	3	4						12	bracken	fallen logs	Sol			Uva	Ass	250		ridges btwn uvalas
Takaka Plateau	15	2501656	6021906												12	pasture/bracken	y	Sol	Ass		Und			072	slope
Takaka Plateau	16	2501508	6021874	052/7SE	2	1	3	2	1		70	32			10	regenerating shrub/natives	C.S.T	Sol	Ass	5-10					slope
Takaka Plateau	17	2501531	6021714		3	2	3	7	2						9	pasture	C.S.T	Uva	Ass	250	Sol			060	polygonal karst
Takaka Plateau	18	2501527	6021633	126/40NE	2	2	0	0	3	3						pasture		Sol	Ass	15-	All			318	saddle between dolines
Takaka Plateau	19	2501256	6021431	126/18NE	1	3	4	2	5						10	regenerating shrub/natives/pines	fallen logs	Sol	Ass					064	doline
Takaka Plateau	20	2501112	6021597	112/26S	0	0	9	3	2		26	78			28	bare karst/some fauna in fract/grikes	fallen logs	Sol	Ass		Uva			188	uvala
Takaka Plateau	21	2501256	6021612	080/22E	3	2	2	0	1	0	82				42	bare karst/some fauna in fract/grikes									
Takaka Plateau	22	2500928	6021574		2	3	3	1	2						12	pasture/regenerating shrub	fallen logs	Und	Ass	20-	Uva			180	uvala
Takaka Plateau	23	2500964	6021345		3	2	5	0	4						28	regenerating natives/wilding pines	fallen logs	Sol	Ass					104	uvala
Takaka Plateau	24	2500845	6022241	238/30S	5	10	3	4	2						14	regenerating natives/bracken	y								
Takaka Plateau	25	2501015	6022259												18	bracken	y								
Takaka Plateau	26	2501155	6022280												21	regenerating shrub/natives	y	Sol	Sym	10-					doline
Takaka Plateau	27	2501310	6022342												12	regenerating natives/pines	y								
Takaka Plateau	28	2501331	6022066												20	beech forest	n								
Takaka Plateau	29	2501182	6022057													remnant bush	some								
Takaka Plateau	30	2501781	6020862	050/68SE	3	2	1	3	1						11	pasture/regenerating shrub	y	Sol	Irr	10-	Uva	Irr	400	090	uvala side

Karst Zone	Sample	Karren type										Macro landform	Comments
	No	Type	Size	Length	Other	Type	Size	Lengt	Type	Size	Length		
Takaka Plateau	1	rund										ridge top	some soin enlargement of diaclases, reasonable soil cover, scattered outcrop
Takaka Plateau	2	rund	10-20	<0.5	mod formed	kamen						uvala	fractured outcropping karst, poss frost action processes, thin soil cover throughout outcrops
Takaka Plateau	3	rund	15	<1.0	mod formed	rinn						uvala, basin	saddle between complex doline basins, enlargement of jts/fract
Takaka Plateau	4	rund	15-25	1.0	mod-well formed							basin with soil cover	soil covered basin, apparent ridges of karst across basin, poss basin centred on interbedded sedt, sedt supply??
Takaka Plateau	5	rund	10-25	~1.0	mod-well formed	rinn						ridge	karst outcropping 1.5-2m above ground surface
Takaka Plateau	6	rund	10-20	<1.0	mod-well formed							blind valley	
Takaka Plateau	7	rund	10-20	<1.0	well formed	rinn						blind valley/ridge	ridge across blind valley, sed't cover increasing in valley floor
Takaka Plateau	8	rund	8-20	<1.0	mod formed	rinn						ridge in blind valley	soil cover increasing in valley floor
Takaka Plateau	9	rund	10-20	<0.5								blind valley	soln features, mod formed, soil cover increasing in valley floor, scattered outcrop, doline axis follows local slope
Takaka Plateau	10	rund	10-20	0.5	mod-well formed	rinn						uvala	soil cover increasing in valley floor
Takaka Plateau	11	rund	10-25	<0.5	fract inhibited							ridge	v clastic, brecc'd in places, poss struct assoc Holyoake Canyon, soils organic dk brn with <1cm Ks clasts
Takaka Plateau	12	rund	10-15	1-1.5	well formed	rinn						hill slope	
Takaka Plateau	13	rill	5-6	<0.5	mod formed	rinn	10-15	<1.0	kamen			hill top - slope	
Takaka Plateau	14	rill			occassional	rund	10-20	<1.0	kamen			polygonal karst	mod-coarse crystalline, peak between dolines
Takaka Plateau	15											slope	slope leading to blind valley
Takaka Plateau	16	rund	10-15	<0.5	well formed	rinn						blind valley side, uvala	
Takaka Plateau	17	rund			mod formed	kamen			rinn			polygonal karst	enlargement of jts/diaclases, roack appears flaggy, uvala with dolines on floor and walls
Takaka Plateau	18	rund	25	<0.5		rinn						polygonal karst	Saddle between large complex dolines/blind valley
Takaka Plateau	19	rund			mod formed	rinn						polygonal karst	layering very clear, flaggy, mostly dk brn soils - autogenic?
Takaka Plateau	20	rill	2-6	<1.0	steep	rund	10-12	<1.0	spitz			polygonal karst	dolines, peak between dolines
Takaka Plateau	21	rill	2-8	<0.5		rund	10-30	<1.0	grike	30	>1.0	polygonal karst	peak between dolines
Takaka Plateau	22	rund			poorly formed	rinn						Uvala	med brn-org soil increasing downslope/valley floor, well rounded 3-4cm cobbles in soils, Fe stone <1cm throughout
Takaka Plateau	23	rund			poorly-mod	rinn						uvala	blind valley with dissected doline floor
Takaka Plateau	24	rund	3-20	<0.5	poss rinn	rinn						doline ridge	ridge between dolines, polygonal karst
Takaka Plateau	25											slope	karst obscured by vegetation, med brn soils, allogenic clasts, slope leading to doline
Takaka Plateau	26											doline	occasional outcropping karst, soil cover, med brn
Takaka Plateau	27											blind valley side	med brn soil cover, occasional outcrop, karst obscured by vegetation
Takaka Plateau	28											doline	no visible karst due to vegetative cover, definitely karst area, slope leading to valley
Takaka Plateau	29											ridge	soil covered ridge, karst obscured by vegetation
Takaka Plateau	30	rund	15-30	<1.0	mod-well formed	rinn						uvala	scattered outcrop in complex doline valley, very large feature

Karst Zone	Sample	Easting	Northing	Strike/dip	Fracture Frequency						Dip			Slope	Slope	Vegetation	forest	Doline Type						Strike	Associated landform
	No				1	2	3	4	5	6	1	2	3	Gradient	aspect	type		Type	Morp	Size	Type	Morp	Size	axis	
Canaan South	1	2501017	6027021	140/40SW	4	2	6	4	7		40	60				pasture	C.S.T	Sol	Ass	3-4	All	Ass		052	rolling hills
Canaan South	2	2501010	6026791	190/48S	1	1	0	0	0	3	40	15		20	NE	pasture	C.S.T								
Canaan South	3	2501176	6026790	180/65S	2	0	0	1	1		30	30		25	NW	beech (stocked)	n (stock)								
Canaan South	4	2500864	6027017													pasture	C.S.T	All	Irr	10					dolines follow valley floor
Canaan South	5	2500720	6027015													pasture/scattered beech	some								
Canaan South	6	2500716	6027087											5	N	pasture/scattered beech	some	All	Ass	15				N	cut off meander?
Canaan South	7	2500715	6027239											30	SSW	pasture	y	All	Irr	2-10	Col				active doline enlargement
Canaan South	8	2500719	6027683		0	0	1	0	1	1	20	20	85	28	165	beech (stocked)	n (stock)	All	Irr	5	Sol			175	karst slope
Canaan South	9	2500723	6027961											20	2302	pasture/beech forest edge	y								
Canaan South	10	2500876	6027676											20	200	beech remnant (stocked)	n (stock)								
Canaan South	11	2501025	6027464											16	178	pasture	y	All	Irr	5				120	slope
Canaan South	12	2501023	6027285	360/40W	2	2	2	1	4	3	40	46	20	15	W	pasture	C.S.T	Sol	Irr	4	All				hills/gully/scattered doline
Canaan South	13	2500871	6027467		0	1	1	0	1		85	85		20	310	pasture/scattered beech	fallen logs								
Canaan South	14	2500408	6027684		4	4	2	2	4	5	20	32	20	40	200	beech (stocked)	n (stock)								
Canaan South	15	2500271	6027232													pasture/scattered beech	some	All	Sym	5					shallow bowl, smooth
Canaan South	16	2500106	6027457													pasture/scattered beech	y	All	Ass						follows paleo drainage
Canaan South	17	2500113	6027904													beech (stocked)	n (stock)								
Canaan South	18	2500412	6027957													pasture/scattered beech	y								
Canaan South	19	2500861	6028131											4	040	pasture	y								
Canaan South	20	2501166	6028137													pasture	y								
Canaan South	21	2501006	6028124													pasture	y								
Canaan South	22	2501147	6028370	150/28N	3	4	1	4	1		65	55		50	220	beech forest	n?								
Canaan South	23	2500429	6026841											8	100	pasture	y	All	Ass	5-10				120	rolling hills leading to drainage
Canaan South	24	2500415	6026649	295/10W	1		0	1	0		20	10		22	350	beech remnant (stocked)	n (stock)								
Canaan South	25	2500267	6026646											16	330	pasture	y	All	Ass	10				300	sloping hill leading to drainage
Canaan South	26	2500098	6026617											28	005	pasture/regenerating shrub	C.S.T								
Canaan South	27	2500111	6027012													pasture/scattered beech	y								
Canaan South	28	2500547	6028364		2	2	2	3	1	1	70	60	22			pasture	C.S.T	All	Ass	10-					doline axis follows local slope
Canaan South	29	2500392	6028370											20	005	pasture/scattered beech	C.S.T	All	Ass						minor depressions

Karst Zone	Sample	Karren							Macro landform	Comments
	No	Type	Size	Length	Other	Type	Size	Length		
Canaan South	1	rund	10-20						dry valley/rolling downs	patchy/sporadic outcrop
Canaan South	2	rund	8-15	<1.0					dry valley	old alluvial system, scattered outcrops in pasture
Canaan South	3	rund	15-20	<1.0	follows slope				ridge line	not far from granite contact
Canaan South	4								dry valley	
Canaan South	5								fluvial terrace	slightly rolling area, surrounded on 4 sides by fluvial valleys (now intermittent)
Canaan South	6								fluvial terrace	
Canaan South	7								fluvial valley/dry valley	appear active evolving, sides of doline steep but alluvial sed't, very active removal of sed't, poss sink
Canaan South	8	rund			poorly formed				breakaway leading to sink	small vlly in breakaway, valley tends to sink area at bottom of slope, not very active anymore
Canaan South	9								gully	alluvial sed't slope, large thickness of sed't, tress bulldozed into gullies, bulldozing postdates clearance by 40-50yrs?
Canaan South	10								dry valley	intermittent run, allogenic valley from slope runoff
Canaan South	11								rolling slopes leading to gully	allogenic derived sed't overlying karst, thick deposit
Canaan South	12	rund			poorly formed				hills leading to gully	soil eroded, roots exposed, scattered shrub in between large jt'ed karst blocks
Canaan South	13	rund	5-10	<1.0	follows slope				slope leading to sink area	probable soil loss, ridges exposed near soil line
Canaan South	14	rund			poorly developed				hill	beech trees rooted in thin soil overlying karst, organic layers, lots of twig debris, slope wash
Canaan South	15								abandoned alluvial system	~3-5m sed't exposed in outcrop, abandoned river terrace
Canaan South	16								abandoned alluvial system	dry valley, minor dolines along old paleodrainage, terraces
Canaan South	17								rolling flats	alluvial sed'ts, assumed to be very thick, minor ponding in depressions
Canaan South	18								rolling flats	pasture, trees bulldozed, thick dep't sed't
Canaan South	19								terrace (paleo)	lower terrace very marshy, bulldozed rows of trees
Canaan South	20								sink	allogenic river flowing to seepage area, close to contact, breakaway sink area, blind valley
Canaan South	21								terrace (paleo)	several ponded alluvial dolines on terrace (but not near sample), alluvial terrace
Canaan South	22	rund			poorly formed				sink	sink area, highly jt'ed boulders karst outcrop NB. Sink location moved since last visit.
Canaan South	23								slope	allogenic cover
Canaan South	24	rund			poorly formed				slope towards gully	outcropping karst, organic topsoil, poss large amount of impurities, some allogenic sed't
Canaan South	25								slope	sloping hill leading from ridge to drainage
Canaan South	26								slope	allogenic sed't, yllw brn soils, clasts
Canaan South	27								dry valley	allogenic and /or surface runoff during high rainfall, well defined surface drainage, dolines starting to intersect drainage
Canaan South	28	rund	10-15	<1.0	poorly formed				blind valley	intermittent flow, dolines intersecting alluvial system, well defined drainage, some sink occurs
Canaan South	29	rund		<0.5	scattered				sink breakaway	intermittently active, interpreted previous activity greater than at present, Ks derived sed't

Karst Zone	Sample	Easting	Northing	Strike/dip	Fracture Frequency						Dip			Slope	Slope	Vegetation	Deforested	Doline Type						Strike	Associated landform
	No				1	2	3	4	5	6	1	2	3	Gradient	aspect	type		Type	Morp	Size	Type	Morp	Size	axis	
Canaan North	1	2501140	6028920												6	pasture	C.S.T	All	Ass	10				330	smooth shallow
Canaan North	2	2501150	6028990												14	beech remnant (stocked)	n (stock)	Sol	Sym	3-15					sloping
Canaan North	3	2501370	6029140		6	8	7	7	6	8	75	5	72	85	16	pasture	C.S.T	Sol			All	Ass	1-15		dry valley side
Canaan North	4	2501750	6029130		2	4	4	1	2		30	30	35			pasture	C.S.T	Sol	Ass	20				315	dry valley floor
Canaan North	5	2501810	6029980													pasture/bracken	C.S.T	Uva			All	Irr	2-10		drainage system
Canaan North	6	2501810	6028810		3	6	4	4	4		40	40	70			pasture	C.S.T	Sol	Sym		All	Ass			ridge line
Canaan North	7	2501980	6028820												10	pasture	y	All	Sym	8					dry valley side
Canaan North	8	2502040	6028980												18	pasture	y	All	Irr	10-					dry valley side
Canaan North	9	2501820	6029290													pasture	y	All	Irr					NW	dry valley floor
Canaan North	10	2501760	6029590	278/80W	0	2	2	0	2		20	20	52		28	pasture	C.S.T	Sol	Irr	10	Uva				dry valley
Canaan North	11	2501820	6029580													pasture	y								
Canaan North	12	2502000	6029430												25	pasture	y								
Canaan North	13	2502030	6029580												5	pasture	y								
Canaan North	14	2502270	6029710													pasture/regenerating shrub	fallen logs								
Canaan North	15	2502260	6029580													pasture	y	All	Irr	25					valley floor, doline shallow ~1m
Canaan North	16	2502260	6029420	348/70N	3	3	1	5	4		45	40	45		30	pasture	y								
Canaan North	17	2502040	6029730		3	0	4	4	4	2	40	80	60	55	8	pasture/regenerating shrub	y	Sol	Irr		All	Irr			fan slope
Canaan North	18	2502030	6029880	050/60NE	3	3	3	2	0	3	50	48	50			pasture/regenerating shrub	fallen logs	Sol	Irr	10					ridge line/side
Canaan North	19	2501590	6029890												8	pasture/scattered beech	some	Sol	Sym	5					slope, doline 3-4m deep
Canaan North	20	2501370	6029740												16	regenerating shrub	y	Sol	Sym	5					sloping hill leading to Canaan
Canaan North	21	2501590	6029580	070/50NE												pasture/regenerating shrub	y	Sol			All				valley side
Canaan North	22	2500922	6028898	160/40E	3	1	1	1	0							pasture	y	Sol	Irr	30-					cave entrance (Dogleg)
Canaan North	23	2500933	6029213		12	7	14	8	4						28	pasture	y								
Canaan North	24	2501188	6029446		4	6	8	2	0							pasture	C.S.T	Sol	Ass						dry valley
Canaan North	25	2501353	6029470		7	4	2	4								pasture	y	Sol	Irr	2-10	All	Irr	2-10		dry valley

Karst Zone	Sample	Karren type							Macro landform	Comments
	No	Type	Size	Length	Other	Type	Size	Length	rolling hills	close to Oma/Ks contact, ponding in dolines, reeds/swamp
Canaan North	1								slope	possible solutional dolines, sed't cover, deeper, sharper profile, point drainage in botttoms
Canaan North	2								dry valley side	fractured karst unit, minimal soln feature, lots of dolines follow local slope
Canaan North	3	rund	<15	<0.5	poorly formed				dry valley	soln doline in valley floor against side, poss previous sink, blocky debris in doline
Canaan North	4	rund			poorly formed				dry valley	sink up against side of valley walls, significant sed't on valley sides, ponding, complex doline bottom
Canaan North	5								ridge	joints not well enlarged, ridge in between two valleys
Canaan North	6	rund			few runnels				dry valley side	shallow sedt filled doline, contact nearby, bulldozed logs
Canaan North	7								dry valley side	bulldozed piles pushed in to dolines, allogenic clasts on slope, contact nearby
Canaan North	8								dry valley floor	alluvial sed'ts, bulldozed trees, ponding of water in drainage system
Canaan North	9								dry valley, paleo sink	large edge of dry valley face, large alluvial system, flat bottom, steep sides, abandoned sink area, small
Canaan North	10	rund	10-20	<0.5	on jointing plane				dry valley floor	dolines in alluvial valley floor, predominantly against ridge/floor contact, intermittent flow?
Canaan North	11								slope	buried karst, thick alluvial dep't, bulldozed piles, regenerating shrub in doline debris
Canaan North	12								fan surface	fan leading in to dry valley, bulldozed piles of logs, eroded toe of fan
Canaan North	13								sink	homestead sink area, large breakaway, close to allogenic Ks contact
Canaan North	14								dry valley	dolines along valley floor
Canaan North	15								ridge behind blind valley	close to contact, bulldozed at least 30 yrs, close to homestead
Canaan North	16	rund	10-30	<1.0	some rillen?				fan surface	soln doline on edges aligned in drainage, alluvial dolines on fan surface, fallen trees
Canaan North	17	rund			poorly formed				ridge	outcropping ridge, soil covered, deforestation
Canaan North	18	rill	~5	~0.2	developing?	rund	20-30	<1.0	slope leading to valley sides	on edge of ATNP boundary, few karst features, buried karst, near contact?
Canaan North	19								slope	qtz boulder, solution, steep dolines, small scattered karst outcrop
Canaan North	20	rund			vegetation				valley side/slope	sandstone bed outcropping, interbedded with Oma, rund parallel to valley orientation, poss structure
Canaan North	21	rund	10-20	<1.0					dry valley/cave	cave entrance still intermittent sink, gravel from Ks at entrance, near Ks contact?
Canaan North	22	rinn			poorly formed	rund			dry valley	slope leading to dry valley
Canaan North	23	rinn	15	<0.5	mod formed				dry valley	fract limiting karren development, prob abandoned sink in dry valley
Canaan North	24	rinn			mod formed	rund			dry valley	fluvial valley, large flat floor, thick sedt on east side, more scour west side, karst canyon?
Canaan North	25	rinn			well formed	rund			ridge top	some soln enlargement of diaclases, reasonable soil cover, scattered outcrop

Karst Zone	Sample	Easting	Northing	Strike/dip	Fracture Frequency						Dip			Slope	Slope	Vegetation	Deforested	Doline Type						Strike	Associated landform
	No				1	2	3	4	5	6	1	2	3	Gradient	aspect	type		Type	Morp	Size	Type	Morp	Size	axis	
Pikikiruna	1	2500692	6021810	128/38NE	2	4	2	3	3						20	pasture/regenerating shrub	fallen logs								
Pikikiruna	2	2500547	6022026												12	pasture	y	Und	Ass	5-10					blind valley
Pikikiruna	3	2500535	6022250	224/20NW	2	0	4	2								pasture	fallen logs	Und	Ass	5-10					uvala/pjole
Pikikiruna	4	2500388	6022248	236/20NW	2	1	3	3	5		30	24			10	pasture/regenerating shrub	some	Und	Ass	4				072	
Pikikiruna	5	2500374	6022300												21	beech forest	n								
Pikikiruna	6	2500383	6021804												5	pasture	y	All	Ass	15-				200	blind valley floor
Pikikiruna	7	2500249	6021570		4	5	7	5			14				14	pasture/regenerating shrub	y	All	Ass	10-	Sol	Ass			blind valley system
Pikikiruna	8	2500243	6021339												20	pasture	y								
Pikikiruna	9	2500403	6021350													pasture	y	All	Ass	20				118	blind/dry valley
Pikikiruna	10	2500549	6021348	060/16E	2	3	6	0	2		44				6	pasture/shrub	y	All	Sym	8-10					slopes
Pikikiruna	11	2500550	6021628												12	pasture/regenerating shrub	y	All	Ass	3-5	Col		<1		doline basin
Pikikiruna	12	2500549	6021798	064/16E	10	3	2	2	5						10	pasture/regenerating shrub	y	All	Irr	5-15					sloping ridge
Pikikiruna	13	2500691	6022700													pasture/regenerating shrub	y	Sol	Irr	3-15	198				valley
Pikikiruna	14	2500692	6022463	068/36NW	0	0	2	2	3						11	pasture/regenerating shrub	y	All	Ass	5-12	Sol	Ass			slope
Pikikiruna	15	2500678	6022930	126/12N	2	2	4	1	2		12				16	pasture/regenerating shrub	fallen logs	Sol	Ass					134	blind valley
Pikikiruna	16	2500229	6022918												10	pasture	C.S.T	Sol	Irr						blind valley
Pikikiruna	17	2500228	6022789	124/24NE	4	1	2	1							22	regenerating shrub, pines	C.S.T								
Pikikiruna	18	2500464	6023060	142/48NE	5	5	2	6	10		48	65				bare karst/some fauna in fract/grikes	y	Und	Ass	10				136	
Pikikiruna	19	2500103	6020802												10	pasture/scattered beech	y	Sol	Ass	5-20					blind valley
Pikikiruna	20	2500235	6020886		3	0	1	3							32	pasture/pines	y	Sol	Sym	8-10					saddle
Pikikiruna	21	2500175	6021404												2	pasture	y								
Pikikiruna	22	2499758	6021448												18	pasture	y								
Pikikiruna	23	2499720	6021663	328/46NE	1	1	0	2	1						26	regenerating shrub	y	Sol	Sym	100					doline side
Pikikiruna	24	2499354	6021964	044/26E	3	0	2	2			26					grasses	y								
Pikikiruna	25	2500466	6021250												11	pasture	y	All	Ass	8				162	valley
Pikikiruna	26	2500261	6021114												16	pasture/regenerating shrub	y	Sol	Ass	10	All	Ass		206	minor blind valley
Pikikiruna	27	2500249	6021093													pasture/scattered beech	y	Sol	Ass	30				168	doline on saddle
Pikikiruna	28	2500484	6020940													pasture	y	All	Ass					146	blind valley minor
Pikikiruna	29	2500698	6020797													pasture, gravel, roading	y	Und	Irr	350					abandoned sink?
Pikikiruna	30	2500698	6020942	342/50NE	2	3	2	1							18	pasture/regenerating shrub	y	All	Sym	10					slope

Karst Zone	Sample	Karren type										Macro landform	Comments
	No	Type	Size	Length	Other	Type	Size	Lengt	Type	Size	Length		
Pikikiruna	1	rund			poorly-mod	rinn						slope	sporadic outcropping karst, calcite nodules/veins, mod coarse crystalline, soil cover
Pikikiruna	2											blind valley	blind valleys, dolines predominantly aligned down valley, outcrop on ridges only
Pikikiruna	3	Rund	10-30	<1.0	well rounded	rinn						Pjole?	multiple blind valleys leading to doline field, some doline steep sided with outcrops of karst, others smooth shallow soil
Pikikiruna	4	Rund	8-20	~1.0	well formed	rinn						Blind valley side	slope leading to blind valley, outcropping karst on soil covered hill
Pikikiruna	5											slope	slope leading to blind valley, forest debris, overland flow, organic soil, no visible outcrops
Pikikiruna	6	Rund				rinn						Blind Valley	blind valley, perpendicular to bedding?, ridge of karst across valley, soil covered
Pikikiruna	7	rund	8-15	<0.5	starting to sharp	rinn						Blind valley	soils covering valley, outcropping karst throughout, jts/fract enlarged, allogenic soil
Pikikiruna	8											Covered karst	probable large thickness allogenic soils, Ks, qtz rich sed't coarse frags, alluvial dep't, some dolines so still in karst
Pikikiruna	9											Blind valley	dolines in bottom of valley, large continuous allogenic soil cover
Pikikiruna	10	rund			minor	rinn						slope	valley/pjoles? Dolines on either side of rise, outcrop karst on sides, most sed't covered
Pikikiruna	11	rund				rinn						uvala	alluvial dolines aligned in sol sink doline basin, collapse doline covered by farmer, allogenic soils, non karst clasts
Pikikiruna	12	rund			poorly formed	rinn						ridge	some outcrops with alrge calcite veins, slope poss affected by bulldozing
Pikikiruna	13	rund			where exposed	rinn						blind valley	valley leading to blind valley, karst outcropping on ridges, soil inc in valley floor
Pikikiruna	14	rund	10-15	<1.0	well formed	rinn						blind valley	shallow smooth depressions and sol steeper dolines with outcrop within sink, good soil cover
Pikikiruna	15	rund	15	<0.5	well formed	rinn						blind valley	steep sides, outcropping karst on sides, soil inc in valley bottom, ponor at end of valley
Pikikiruna	16	rund			well formed	rinn						blind valley	abandoned or intermittent sink, sloping allogenic cover, 5-8 m karst breakaway, swiss maid valley
Pikikiruna	17	rund	10-20	<0.5	well formed	rinn						blind valley	well exposed karst on ridges, soil cover inc downslope
Pikikiruna	18	rund	10-40	<1.0	well formed	rinn						blind valley	
Pikikiruna	19											blind valley	steep sided soil covered doline, predominantly soil covered area, occasional outcrop, near sawmill sink area
Pikikiruna	20	rund			mod formed	rinn						saddle/valley	scattered outcropping karst in saddle btwn valleys. Btwn Hikis (abandoned) and sawmill (active)
Pikikiruna	21											slope	slope leading to blind valley, soil covered (>3m) org brn allogenic soils
Pikikiruna	22	rund			where exposed	rinn						slope	soil sed't covered slope, yllw brn soils, leading to soil covered blind valley, occasional outcrop
Pikikiruna	23	rinn	10-15	<0.5	mod formed							doline	slope leading to doline, predominant soil covered org brn soils angular clasts in soil
Pikikiruna	24	rinn			poorly formed	rund						blind valley	forestry 1980's skid pas, some soln along diaclases, human impact recent NB caves
Pikikiruna	25	rinn			where exposed	rund						slope	slope, doline aligned along blind valley, probably connected valley to sink (Hikis), rolling hills
Pikikiruna	26	rinn			where exposed	rund						doline/blind valley	minor blind valley, no active alluvial drainage
Pikikiruna	27											doline	doline, valley drainage system, numerous dolines leading towards, aligned in valley
Pikikiruna	28											blind valley	blind valley, dolines, no active alluvial drainage
Pikikiruna	29											Sink, Quarry	Hikis quarry (personal usage) poss abandoned sink would lead to Riwaka Source
Pikikiruna	30	rinn			poorly formed	rund						small dry valley	bedding impurities in Oma, edge of zone, autogenic rich brn soils coming from ridge behind?, nr Hikis' sink

Karst Zone	Sample	Easting	Northing	Strike/dip	Fracture Frequency						Dip			Slope	Slope	Vegetation	Deforested	Doline Type						Strike	Associated landform
	No				1	2	3	4	5	6	1	2	3	Gradient	aspect	type		Type	Morp	Size	Type	Morp	Size	axis	
Takaka Walkway	1	2498838	6019545	028/36E	3	2	4	6	2	2	30	40	40	25	270	pasture/regenerating shrub	y								
Takaka Walkway	2	2498656	6019228		3	3	4	4	3					14	086	pasture/regenerating shrub	fallen logs	Sol	Ass	40	Col	Irr	<1	062	Doline basin
Takaka Walkway	3	2498842	6019074	080/54SE	9	8	7	7						20	340	pasture/regenerating shrub	fallen logs	Sol	Ass	25	Col	Irr	<1	094	doline basing nr sd/st contact
Takaka Walkway	4	2498888	6019078		6	5	1	4	3		55	30				beech forest	n (past	Col	Sym	2					basin
Takaka Walkway	5	2499062	6018940		0	2	6	8	2	8						Forest/ regenerating undergrowth	n (past	Sol			Col	Irr	4		small basin/steep collapse
Takaka Walkway	6	2499288	6018789		4	6	2	8	9	3						pasture/regenerating shrub	fallen logs	Und							Basins
Takaka Walkway	7	2499291	6018641	320/80NE	6	4	0	8	12	7	80			16	348	pasture/regenerating shrub	C.S.T	Sol	Ass	8	Col	Irr	1	328	Basin
Takaka Walkway	8	2499072	6018331		7	6	3	1	5					18	005	regenerating shrub - extensive	fallen logs	Col	Irr	1.5					slope side leading from ridge
Takaka Walkway	9	2498936	6018788											4	360	pasture/regenerating shrub	fallen logs	Und	Irr	2					depression
Takaka Walkway	10	2498832	6018787											8	260	pasture/regenerating shrub	fallen logs								
Takaka Walkway	11	2498780	6018638		9	5	11	6	9		85	80	76	18	224	bare karst/some fauna in fract/grikes	fallen logs								
Takaka Walkway	12	2498614	6018643		12	3	10	6	6	9	32	80		5	014	bare karst/some fauna in fract/grikes	fallen logs								
Takaka Walkway	13	2498613	6018479		2	2	2	2						44	064	beech forest	n	Sol	Ass	20				350	doline/poss abandoned sink
Takaka Walkway	14	2498611	6019395											32	120	beech	n (past	Sol							
Takaka Walkway	15	2498610	6019237		5	21	7	10	6		29	38	46	58	316	pasture/regenerating shrub	some								
Takaka Walkway	16	2498621	6019071	258/44NW	4	10	13	5	3					16	180	regenerating shrub	C.S.T	Sol	Sym	20	Col	Irr	1.5		slope
Takaka Walkway	17	2498612	6018938		3	10	8	6	1					16	174	pasture/regenerating shrub	C.S.T								
Takaka Walkway	18	2498388	6018779													pasture/regenerating shrub	C.S.T	Sol	Sym	5					small basin, doline drainage
Takaka Walkway	19	2498389	6018632		10	7	8	8						16	342	pasture/regenerating shrub	C.S.T								
Takaka Walkway	20	2498394	6018483											16	084	beech forest	n								
Takaka Walkway	21	2498174	6018642	074/44S	12	7	4	8			44					bare karst/some fauna in fract/grikes	fallen logs								
Takaka Walkway	22	2498175	6018335											29	292	beech forest	n (track close)								
Takaka Walkway	23	2497717	6018337	080/28E	6	11	12	9	4		84	30	80	26	210	bare karst/some fauna in fract/grikes	fallen logs								
Takaka Walkway	24	2497727	6018632	092/38S	8	7	6	7			48			8	282	pasture/regenerating shrub	C.S.T								
Takaka Walkway	25	2497941	6018782		3	2	2	4	3					26	164	bare karst/some fauna in fract/grikes	fallen logs								
Takaka Walkway	26	2497936	6018932											22	328	pasture/shrub/isolated tree	y								
Takaka Walkway	27	2498143	6018938		3	7	4	11						24	069	pasture/regenerating shrub	fallen logs	Sol	Ass	100	Col	Irr	3		
Takaka Walkway	28	2498256	6018935													pasture/regenerating shrub	fallen logs	Uva	Irr	30					4 dolines forming floor
Takaka Walkway	29	2498221	6019091		8	6	9	12	8					20	182	regenerating shrub	fallen logs								
Takaka Walkway	30	2498389	6018936	056/44E	4	4	10	3	7		42			2	196	bare karst/some fauna in fract/grikes	fallen logs								

Karst Zone	Sample	Karren type										Macro landform	Comments
	No	Type	Size	Length	Other	Type	Size	Lengt	Type	Size	Length		
Takaka Walkway	1											slope to summit sink	Near contact of Oma/Schist
Takaka Walkway	2	rund	10-12	<0.5	poorly formed							doline basin	little sol'n features, mosses appear to grow preferentially in fractures, brecciated appearance
Takaka Walkway	3	rund	10-20	0.5-1.0								doline basin	soln runnels, clastic appearance, concentration of sed't in basin, basin follows strike of bedding, sd/st outcrop (insitu)
Takaka Walkway	4											basin with collapse doline	some enlargement of joints, doline basin (30m) shallow with collapse doline within ~3-4m deep
Takaka Walkway	5	rund			poorly formed	rinn						basin with collapse doline	very fractured karst, diameter of trees diff/stringy bark/poss original remnant (due to lack of soil?)
Takaka Walkway	6	rund			rounded blocks							basin with collapse doline	occasional soln features, basins accumulation of soils, shallow depressions, yllw-brwn soils
Takaka Walkway	7	rund	5-10	<0.3	small	rinn						basin with collapse doline	poss autogenic point source, enlarged joints in orientation of doline, boulders in col doline floor
Takaka Walkway	8	rund	10-20	<0.5		rinn						slope	orange-sd/st-brown soils increasing downslope, outcropping karst on ridge
Takaka Walkway	9	grike	0.3	~1m								depression	karst outcropping in centre of depression, grikes with soils, soil erosion, enlarged joints
Takaka Walkway	10	Rinn			poorly formed	rund						basin with soil cover	occasional outcrop only, soil obscures karst, large tree diameter than in sample 5.
Takaka Walkway	11	Rill	1-2	<0.5	well formed	rund			Grik	15-30	1-2	ridge	frost shattering??, tree roots 20-30cm above bare rock surface, soil erosion
Takaka Walkway	12	rund	10-20	<0.5		grike	10-20	1-2				slope/ridge	very brecciated karst
Takaka Walkway	13	rund			covered							doline	poss abandoned sink area, doline very steep on one side, small valley leading to doline
Takaka Walkway	14											Sink	summit sink/close to fault or contact
Takaka Walkway	15	rund			poorly formed							sink/breakaway	little soln features, poss collapse cliff above summit sink, a lot of toppled blocks, some rounding of exposed karst
Takaka Walkway	16	rund				rinn						slope side of basin	enlargement of fract/brecciated appearance, many diaclases, jagged
Takaka Walkway	17	rund	10-15	<0.5								slope	very clastic, mosses growing in fract, sporadic outcrop of karst in soil filled basin, mod soil cover
Takaka Walkway	18	rund										slope, small basin	sporadic outcrop of clastic karren in pasture, soil covered, enclosed shallow basin
Takaka Walkway	19	rinn			poorly formed	rund						slope	breccaited karst, scattered outcrop, soil orange-brown, clast rich
Takaka Walkway	20											slope	slope leading towards doline in bush, no outcrop of karst showing, covered with organics and soil
Takaka Walkway	21	rill	5-8	<0.5	occasional	rund	5-20	<0.5	Grik	10-20	~0.5-1	ridge	blocky, fractured, rubbly, soil erosion, tree exposed roots
Takaka Walkway	22											slope	no karst outcropping, brown soils, humus layer, rendzina soils exposed in nearby track cut
Takaka Walkway	23	rill			poorly formed	rund	10-20	<1.0	Grik	50	1-2	fault escarpment cliff top	enlarged jts, grikes parallel to cliff edge/fault
Takaka Walkway	24	rund	3-5	<0.5	mod formed							slope	fractured outcropping karst out of soil cover-grasses
Takaka Walkway	25	rill	1-2	<0.2	where < fractured	rund	10-20	<0.5	Grik			slope leading to basin	well formed soln features exposed, very brecciated, rillen forming on less fractured rock
Takaka Walkway	26	rund	20-40	<1.0	mod formed							slope leading to scarp	blocky outcrop of karst in soil covered slope, rendzina soils present
Takaka Walkway	27	rund			minor							slope leading to basin	outcropping karst/soils
Takaka Walkway	28	rund			where exposed							large basin	soil cover in basin increasing downslope, large smooth feature
Takaka Walkway	29	rund	10-20	~50	mod-well formed							slope	good outcrop on slope, soils in between outcrops, burnt debris
Takaka Walkway	30	rund				grike						slope	rubbly outcrop, sharp, clastic appearance

Karst Zone	Sample	Easting	Northing	Strike/dip	Fracture Frequency						Dip			Slope	Slope	Vegetation	Deforested	Doline Type						Strike	Associated landform
	No*				1	2	3	4	5	6	1	2	3	Gradient	aspect	type		Type	Morp	Size	Type	Morp	Size	axis	
East Takaka	1	2498110	6035121		4	5	4	6	3						32	pasture	y								
East Takaka	2	2497882	6034983		4	5	8	3	4						18	pasture/shrubs/bracken	y								
East Takaka	3	2497899	6035291												10	pasture	fallen logs	All	Sym	30					blind valley
East Takaka	4	2497660	6035220	346/24NE	1	4	0	2							20	pasture	y	Und	Ass	<2					slope
East Takaka	5	2497653	6035412		2	2	1	2	1						26	pasture	?								
East Takaka	6	2497638	6035576		5	5	6	2	4						24	pasture	y								
East Takaka	7	2497890	6035741		8	6	2	10	7		62	44			30	shrub, grasses	y								
East Takaka	8	2498108	6035424	024/58NE	4	5	3	5	3						10	pasture, shrub, thistles	y								
East Takaka	9	2498322	6035585												32	pasture	y								
East Takaka	10	2498349	6035398		1	2	1	2							30	pasture	y								
East Takaka	11	2498342	6035109												30	pasture	y								
East Takaka	12	2498557	6035090	226/23NW	2	2	4	1	2						10	pasture	y								
East Takaka	13	2498555	6035279		3	5	8	7	2						32	pasture/occasional totara/shrub	y								
East Takaka	14	2499031	6034676	348/84	2	2	5	6	3							pasture/regenerating shrub	C.S.T	Sol			Col	Irr	<1.0		basin
East Takaka	15	2499005	6035147		25	4	0	1	3		90				16	pasture/regenerating shrub	C.S.T	Sol			Col	Irr			ridge
East Takaka	16	2498794	6035152	354/84W											38	grasses, shrub	y								
East Takaka	17	2498808	6034810		7	3	2	10	2						30	pasture/regenerating shrub	C.S.T								
East Takaka	18	2497168	6032751	154/40NE	4	2	7	4	1						28	pasture	y								
East Takaka	19	2499156	6034532		9	8	5	0								pasture	C.S.T	All	Ass	30-	Col	Irr	1-4		poss polygonal karst

Karst Zone	Sample	Karren type										Macro landform	Comments
	No	Type	Size	Length	Other	Type	Size	Lengt	Type	Size	Length		
East Takaka	1	rinn			poorly formed	rund						slope	outcropping karst, toppled blocks, steep slope leading to canyon/dry valley, poss intermittent flow
East Takaka	2	rinn			poorly formed	rund						dry valley	generally fractured, fract poss inhibiting soln features, outcropping karst sporadic, good soil cover, rolling hills on ridges
East Takaka	3											blind valley	rolling hills on escarpment edge, good soil cover
East Takaka	4	rill			where exposed	rund						slope	occasional outcrop of karst on soil covered escarpment front
East Takaka	5	rinn			poorly formed	rund						escarpment/slope	steep slope, poss no large trees only shrub?????, occasional outcrop on slope, flaggy appearance
East Takaka	6	rinn			poorly formed	rund						escarpment/slope	toppled blocks indicating some collapse
East Takaka	7	rinn			poorly formed							escarpment/slope	very fractured, brecciated, poss inhibits solution features
East Takaka	8	rinn			sharpening							ridge	fractured, flaggy rock, rinnen becoming sharpened, some enlargement of jts/diaclases
East Takaka	9											dry valley side	occasional outcrop/subcrop, soil cover, dk brn black, steep sided valley wall leading to dry valley
East Takaka	10	rinn			mod formed	rund						dry valley side	slope leading to dry valley, soil cover
East Takaka	11											slope	close to gabbro contact, slope, peak small valley
East Takaka	12	rinn			mod formed	rund						blind valley	peak between blind valleys either side, Gabbro contact near, coil cover
East Takaka	13	rund				rinn						dry valley ridge	fractured outcrop/subcrop, brecciated, angular, poorly developed soln features, soil cover
East Takaka	14	rinn			mod formed	rund						ridge	ridge with 'the basing and dry vlly either side, fine dense Oma, calcite, flaggy appearance
East Takaka	15	rinn	8-15	<0.5	mod-well formed	rill						dry valley/basin	soil cover inc downslope, small fault nearby 166/90° karren becoming sharper
East Takaka	16	rinn			sharpened	rund			spitz			dry valley side	fractured, enlarged joints
East Takaka	17	rinn			poorly formed	rund						dry valley side	soil cover increasing downslope
East Takaka	18	rund										dry valley	roading through Oma, farm track, small catchment for reasonable size valley/canyon
East Takaka	19	rill			mod formed	rund						plateau in fluvio area	areas with incr fract, have less karren development, basin with tomos scattered throughout

*Samples number limited by access

Karst Zone	Sample	Easting	Northing	Strike/dip	Fracture Frequency						Dip/strike structure			Slope	Slope	Vegetation	Deforested	Doline Type			Associated landform
	No				1	2	3	4	5	6	1	2	3	Gradient	aspect	type		Type	Morp	Size	
Pohara	1	2500376	6041027		6	3	0	0	8	2						pasture	y	Sol	Sym	30	cave entrance, headwall
Pohara	2	2500403	6040912		2	2	1	4	1	2				20	098	reveg woodland	?	Sol	Ass	30	slope leading to dry ck
Pohara	3	2500662	6041163		2	0	3	0								grass, shrubs, gorse	y	Sol	Ass	50-80	slope leading to doline
Pohara	4	2500481	6041163	240/10S	5	2	4	3								road edge	y				
Pohara	5	2500430	6041057		3	1	4	2	2	1	210	210	280	30	SW	leaf litter	n	Sol	Ass	6-10	follows grike
Pohara	6	2500488	6041581		6	4	7	1								forest litter	n				
Pohara	7	2500579	6041644		3	0	0	0	2	0	220	310	270	30	N	forest litter	n				
Pohara	8	2500849	6041625		2	3	0	1						15	NW	reveg forest	y				
Pohara	9	2501048	6041670		2	2	1	0								leaf litter	n				
Pohara	10	2501137	6041409		5	3	4	2	4	1	20					grass	y				
Pohara	11	2501182	6041291													grass	y	All	Irr	20	nr knoll
Pohara	12	2501767	6042691		5	2	2	1	2	0				25	N	reveg shrub	y				
Pohara	13	2499017	6039782	240/40E	0	1	0	0	4	2	250	260	170			forest	n				
Pohara	14	2499111	6039895		9	2	10	4	3	4	15					pasture	y				
Pohara	15	2501769	6041211		3	4	2	4	2		20										
Pohara	16	2501709	6041082	220/20NW	3	4	2	4	2							reveg bush	y				
Pohara	17	2499256	6039615		2	0	2	3	2							road cut	y				
Pohara	18	2499256	6039615													pasture	y	Sol	Ass		slope to valley
Pohara	19	2498642	6038635													pasture	y				
Pohara	20	2499471	6039197		0	1	3	2	2	2				25	NW	reveg bush	y				
Pohara	21	2500234	6040699	225/30W	3	2	3	0	3	4				30	W	pasture	y	Sol	Ass	50	lst escarp
Pohara	22	2497362	6037088	228/40W	3	5	3	7	4					40	NW	pasture	y				
Pohara	23	2497555	6037465	220/45W	5	3	2	1	4	1				45	W	pasture	y	Sol	Ass	20	escarp slope
Pohara	24	2500110	6040771													pasture	y	Sol	Ass	30	valley floor
Pohara	25	2500197	6040360	300/10S	1	0	5	3	6	2	10					pasture	y	Sol	Ass	10	gully bottom
Pohara	26	2500286	6040107													pasture	y				
Pohara	27	2500712	6040435													pasture	y				
Pohara	28	2500496	6040884	245/15S	3	6	2	2								pasture	y				
Pohara	29	2501481	6042584	300/20S	0	0	2	1	1	0						remnant vege	n				

Karst Zone	Sample	Karren type										Macro landform	Comments
	No	Type	Size	Length	Other	Type	Size	Lengt	Type	Size	Length		
Pohara	1											styolite flaggy	Headwall, sinkholes along base of wall.
Pohara	2	rund			poorly formed							slope	rock outcrop on 3 sides, qt vert on several sides.
Pohara	3	rund	10-15		poorly formed	kamen	10-20					slope, behind Po	area modified by subdivision
Pohara	4	rund			mod formed							slight headwall	trees filling in rund deep down into sectional profile. Doline focused around base of small headwall
Pohara	5	rund			wallkarren/vert	grike						grike, clint area	elongated roots along grikes, algae-moss on wall where no light, nr to headwall area
Pohara	6	rinn			v. occasional	rund			sol			styolite flaggy	on Peacock Rock, preferential weathering of rock esp along styolites
Pohara	7	rund			half pipe on wall	rill			grike			styolite, pref weathering	
Pohara	8	rund										styolite	slope leading from cliff. Some layers more sandy, some v fossil, preferential weathering
Pohara	9											styolite	headwall bottom, stream running at foot, permanent
Pohara	10	rinn			where exposed	kamen	<10					styolite	slope, chimneys, pipes present, moss growing in styolite, some enlargement
Pohara	11											smooth slope	
Pohara	12	rund			poorly formed							styolite	slope leading from headwall
Pohara	13	grike				rund			sol				grikes very dominant, in the grove
Pohara	14	rund			on grikes	kamen						styolite	outcrop q flat in amongst cover, v styolitic
Pohara	15												
Pohara	16	rinn			mod formed	rund			sol			Ridge top	
Pohara	17											contact	Btween l/st and mudstone, overturned strat, solutional pitting on vert wall
Pohara	18												slope to valley, qt covered karst
Pohara	19											headwall	cliff, headwall, soil cover, alluvium (Ks), increasing in valley floor, occassional outcrop
Pohara	20	rinn	5-10	<20cm	crest sharp	kamen						slope below ridge	karren forms often controlled by struct, occasional outcrop, Ks derived soils
Pohara	21	rinn	10-30	<20		kamen						escarpment	
Pohara	22	rund				kamen	<10		rund			behind escarpment/ridge	nr to Marble contact, numerous toppled blocks
Pohara	23	rinn	10-20	<.50		rund			kamen	~5	<10	escarp slope	
Pohara	24											plains	flat alliuvium covered area beneath escarp, doline modified by extraction of gravels/quarry
Pohara	25	rund										gully	outcrop in gully floor only, overlain by mudstone
Pohara	26											mudstone cover	no doline in mudst, maybe too thick or too indurated. Karst outcrop on ridges
Pohara	27											ridge slope	mudst sedt cover, small perm stream in gully passes thru watergap in ridges
Pohara	28	rund										headwall	small headwall outcrop of limestone underneath mudst
Pohara	29	rund										headwall	styolitic enlarged joints, sea cliff

APPENDIX B – NON PARAMETRIC STATISTICS (G-TESTS)

Part 1: Chi-squared table

These tables are used for *G* tests.

Procedure: go down rows until you get to the appropriate number of degrees of freedom (df), in this case the degrees of freedom are 7: one less than the number of zones. Then go across columns, checking to see whether $G > \chi^2$ (tabulated). If so, go on to the next column, until $G < \chi^2$ (tabulated). The probability of the null hypothesis (the significance level) is less than the probability of the preceding column (to the left), but greater than the probability of the column where you stopped. If $G > \chi^2$ ($p = 0.001$), then the significance is reported as $p < 0.001$.

df	0.05	0.01	0.001
1	3.84	6.64	10.83
2	6.00	9.21	13.82
3	7.82	11.35	16.27
4	9.49	13.28	18.47
5	11.07	15.09	20.52
6	12.59	16.81	22.46
7	14.07	18.48	24.32
8	15.51	20.09	26.13
9	16.92	21.67	27.88
10	18.31	23.21	29.59
11	19.68	24.73	31.26
12	21.03	26.22	32.91
13	22.36	27.69	34.53
14	23.69	29.14	36.12
15	25.00	30.58	37.70

df	0.05	0.01	0.001
16	26.30	32.00	39.25
17	27.59	33.41	40.79
18	28.87	34.81	42.31
19	30.14	36.19	43.82
20	31.41	37.57	45.32
21	32.67	38.93	46.80
22	33.92	40.29	48.27
23	35.17	41.64	49.73
24	36.42	42.98	51,18
25	37.65	44.31	52.62
26	38.89	45.64	54.05
27	40.11	46.96	55.48
28	41.34	48.28	56.89
29	42.56	49.59	58.30
30	43.77	50.89	59.70

(online ref. www.biology.soton.ac.uk/bs209/fikles/contingency.doc)

Part 2. Doline and karren g-tests

Doline and karren g-test statistical workings are given on the CD (disk) at the rear of this thesis.

APPENDIX C – LITHOLOGICAL SUMMARY RESULTS AND DATA

Part 1. Summary tables

For all tables the 95% confidence interval = Sample Mean +/- 1.96 x SE, assuming a large sample size.

Summary table for porosity analysis.

Karst Zones	Minimum	Maximum	Mean	Std deviation	Std error	Confidence interval (95%)
Kairuru	0.66	3.02	1.55	0.61	0.11	0.22
Plateau Karst	0.42	2.68	1.00	0.53	0.1	0.20
Canaan South	0.69	3.73	1.75	0.87	0.16	0.31
Canaan North	0.53	2.99	1.44	0.74	0.14	0.27
Pikikiruna	0.49	3.37	1.37	0.72	0.14	0.27
Takaka Walkway	0.43	3.75	1.17	0.76	0.15	0.29
East Takaka	0.58	4.08	1.30	0.80	0.15	0.29
Pohara	0.96	13.08	3.26	2.38	0.49	0.96

Summary table for fracture frequency

Karst Zones	Mean	Std deviation	Std error	Confidence interval (95%)
Kairuru	1.8	1.67	0.17	0.33
Plateau Karst	3.0	2.10	0.20	0.39
Canaan South	1.8	1.68	0.20	0.39
Canaan North	3.8	2.88	0.38	0.74
Pikikiruna	2.7	2.09	0.26	0.51
Takaka Walkway	6.0	3.43	0.30	0.59
East Takaka	4.1	3.48	0.41	0.80
Pohara	2.5	1.98	0.18	0.35

Fracture frequency data is presented in Appendix A (geomorphological classification database).

Summary table for lithological purity

Karst Zone	Minimum (%)	Maximum (%)	Mean (%)	Std. Deviation	Std. error	Confidence interval (95%)
Kairuru	0.358	14.224	3.961	4.011	0.732	1.435
Takaka Plateau	0.371	23.325	3.957	5.179	1.016	1.991
Canaan South	0.558	43.854	15.322	11.008	2.044	4.007
Canaan North	0.696	29.342	5.380	5.843	1.124	2.204
Pikikiruna	1.673	15.447	7.187	4.464	0.859	1.684
Takaka Walkway	0.012	8.776	1.743	2.475	0.460	0.901
East Takaka	0.596	9.453	3.460	2.414	0.483	0.946
Pohara	1.849	18.728	7.567	4.954	1.011	1.982

Part 2. Porosity and Purity Database

Data collected from porosity and purity analysis is presented on CD (disk) at the rear of this thesis.

APPENDIX D – SOIL SAMPLING

Figure overleaf: Small soil trenches (30cm3) excavated in the modified and unmodified (control) areas at each of the three soil sampling sites (Takaka Walkway). Site descriptions are given in Chapter three.

Soil sampling data is given in the CD (disk) at the rear of this thesis.

Soil trenches taken as part of soil sampling to determine the impact of vegetation clearance on soil erosion. Non-calcareous soils at undisturbed (1a) and cleared (1b), rendzic soils in undisturbed (2a) and cleared (2b) sites. The most obvious visual impact was the removal of the organic humus after clearance.